# High Technology for Material Processing Based on Welding†

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**Abstract**

*When viewing the recent progress in welding science and technology, it can be seen that such progress is not only due to the development and expansion of existing technology, but also to the integration of individual processes to produce higher level technologies. A variety of new technologies have also come into being based on welding and related fields. In this paper will be reviewed the latest highly integrated welding processes, and also some new technologies based on welding engineering. Some typical examples of advanced welding technologies which will be examined include*

*1) High energy density welding, such as electron beam and laser welding, and*

*2) Welding by robots.*

*Several new technologies will also be discussed to show how integrated welding knowledge can greatly contribute to those areas. These include*

*3) Surface modification or treatment of materials by the use of high energy density heat sources,*

*4) Methods of producing composite materials by modifying conventional welding methods,*

*5) Making substances in different states, such as in amorphous form, ultra fine particles, and so on.*

**KEY WORDS:** (High Technology) (Material Processing) (Welding Technology) (High Energy Density Heat Source)

## 1. Introduction

Welding technology has served as the basis for the development of today's advanced manufacturing technologies. Welding is one of the most important processes used in the production of manufactured parts and goods, and also plays a vital role in most structures. Advanced technical and economic considerations have created a strong demand for the development of high precision, high performance welding techniques and systems in fields ranging from major architectural superstructures to minute electronic components.

Indeed welding engineering consists of many fields of science and technology, and has progressed as a typical inter-disciplinary new field, materialized by the import and accumulation of knowledge and experience from different fields such as shown in **Fig. 1**.

I believe this welding field has recently matured well and been playing an important role in the development of other research fields. We may say it has grown up from the conventional welding body established on the "imported" knowledge, to the new body to be able to "export" various fruitful results to other fields.

Arc heat sources developed approximately a century ago have played a central role in the development of modern welding technology and provided the foundation for today's welding engineering and advanced welding technology, without which the world would never have seen the development of today's shipbuilding, architecture, mechanical, electrical, chemical, metallics, and electronics industries. As the heat sources for welding as well as other heat processing, arc heat sources provide many advantages over other heat sources, including high temperature and high energy density which is ten times that of a gas flame. However, it has become extremely difficult for arc heat sources to keep pace with the technological demands for higher precision, performance, and quality. Material degradation at weld joints, residual stress and strain, and excessive heat input into the material and so on are problems originating from the intrinsic properties of arc heat sources. In other words, the energy density of arc heat sources is still too low for many modern applications, and this has required the development of new heat sources.

To overcome the drawbacks of arc heat sources, the

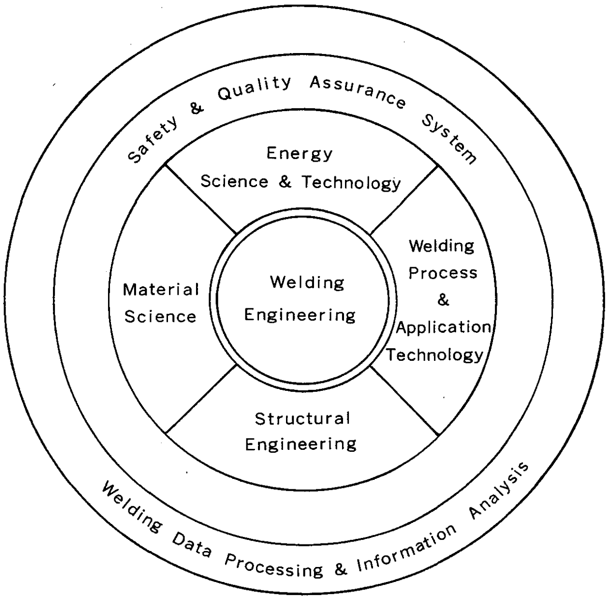


**Fig. 1** Research fields related to welding engineering.

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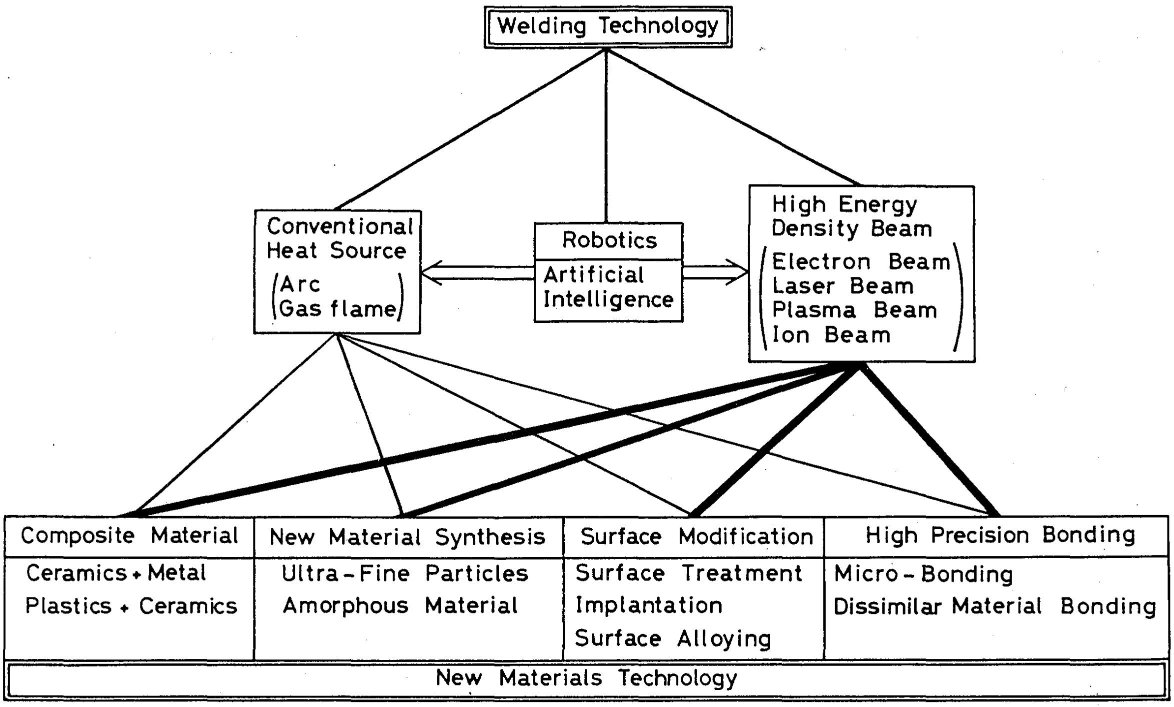



**Fig. 2** New Technology based on welding.

author and his associates initiated research into the development and application of high energy density heat sources exhibiting characteristics quite different from arc heat sources. This research was begun approximately thirty years ago, with the greatest success coming in the last ten years.[1] These new heat sources include electron beams, laser beams and plasma beams.

Many recent advances in welding have come both from the above stated arc heat sources and these new high energy density beam sources. Furthermore, these technologies have been applied not only to welding and cutting techniques, but to the development of other new technologies for heat processing applications.

**Figure 2** illustrates typical applications of these technologies. With two types of heat sources sustaining the development of welding technologies, consistently high precision welding quality has been achieved and welding efficiency maximized through the application of robotics. While, there are a number of new materials technologies as shown in the lower part of the figure gradually reaching a stage of development which will enable practical application in the 21st century. The latest welding engineering can bear a key to contribute to new materials technology with the development of fine control systems for processing. I believe this new trend in welding engineering will cultivate the growth and creation of other new fields. These include, for example, composite materials, and synthesis and qualitative improvement of new materials.

The relative importance of the current relationship between new materials technologies and the heat sources which play an important role in welding engineering is indicated by the thickness of the line. For example, improvement in methods utilizing conventional heat sources will enable bonding of ceramics to metals in the composite materials field. New arc control techniques are also being studied for the manufacture of ultrafine powders in the field of new material synthesis. Furthermore, high energy density beams are being examined with regard to high precision control of heat source for applications in the modification and treatment of other materials.

New materials technologies using high energy density beams are believed essential to the future of advanced control technologies. In this paper will be briefed the technical topics in welding processes using high energy density beams, and will also look at robotics and trends in integrated welding processes. Furthermore, trends in new research topics addressing the development of next-generation materials technologies based on the existing welding technologies will be considered in the context of composite materials and new material synthesis.

## 2. High Energy Density Beam Welding

Advances in welding technologies refered to as the application of thermal energy to material processing paralleled the history of heat source development. Advances in welding heat sources, the first of which utilized the heat of oxidation reaction, have grown steadily in both energy capacity and density through the development and application of electric resistance Joule heat and arc heat sources. Requirements for increasing the power output and energy density of these heat sources still continue to develop and apply ultra high energy density beam heat sources, typified by electron beams, laser beams as electromagnetic energy beams and plasma beams which are illustrated in **Fig. 3**. This section will examine current trends in welding processes utilizing these three high energy density heat sources.

### 2.1 Electron beam welding

Of the three ultra high energy density beams under consideration, the electron beam offers relatively higher output and the greatest ease of generation, and was therefore the first high energy density beam to be commercially applied.

The development of high power output, one major advantage of electron beam heat sources, has grown from the relatively low, several kilowatt power of early electron beam heat source to medium and high output beams generating over 100 kW. Furthermore, low acceleration voltages of less than 100 kV are sufficient for medium output beams, but demand for high output beams requires higher acceleration energy, too. Today 100 kW class electron beam welding machines are available for commercial application.

**Figure 4** shows output of strong focusing type "EBW" apparatuses developed in recent 20 years from 1966 to 1985.[2] Squares show EBW guns for industrial use and circles show those for laboratory works. The solid line gives the maximum power for industrial use at each year. The broken line gives the maximum power in laboratory machine. As shown in this figure, in 1967, 1972, 1974 and 1980, JWRI (Arata Lab.) was the first who developed the highest output machines at each period, and this result later led to the full-scale industrial application of high power, high density electron beams for ultra thick plate welding.

The largest electron beam welding machine currently under development is the 300 kW class (acceleration voltage: 600 kV, maximum beam current: 500 mA) shown in **Fig. 5** and located at the Research Center for Ultra High Energy Density Heat Sources, JWRI.[3] To achieve this high voltage as high as 600 kV, an unique acceleration unit, "multi-stage electromagnetic acceleration unit"[4] developed by the author is used. Single pass welding of ultra thick materials such as steel, aluminum alloys and so on is the developmental objective of this welding equipment. Realization of this objective will increase the thickness of weldable plate, enable super high speed welding, special large-scale castings beyond the reach of conventional welding techniques.

The "Electron Beam Welding Method for Ultra Thick Plates" was realized and established in 1972 for the first in the world at JWRI (Arata Lab.). **Figure 6** shows typical examples obtained by this method.[5]

When these high power electron beams are applied to deep penetration welding, various welding positions are required. In the upper part of **Fig. 7**, a schematic diagram of all position electron beam welding method developed at JWRI is shown.[6] In the lower part, horizontal welding position is shown as an example. Deep penetration welding of ultra thick plates of various materials became possible by this method.

**Figure 8** shows the bead cross sections of 10 cm thick plates in various weld materials obtained by this system.[6]

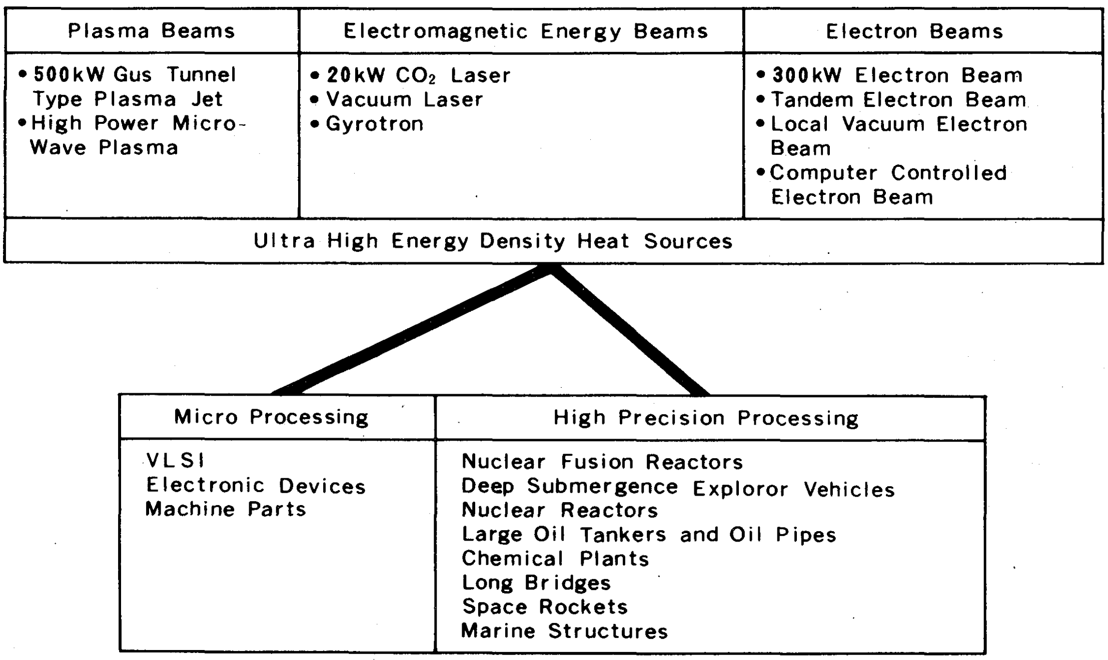
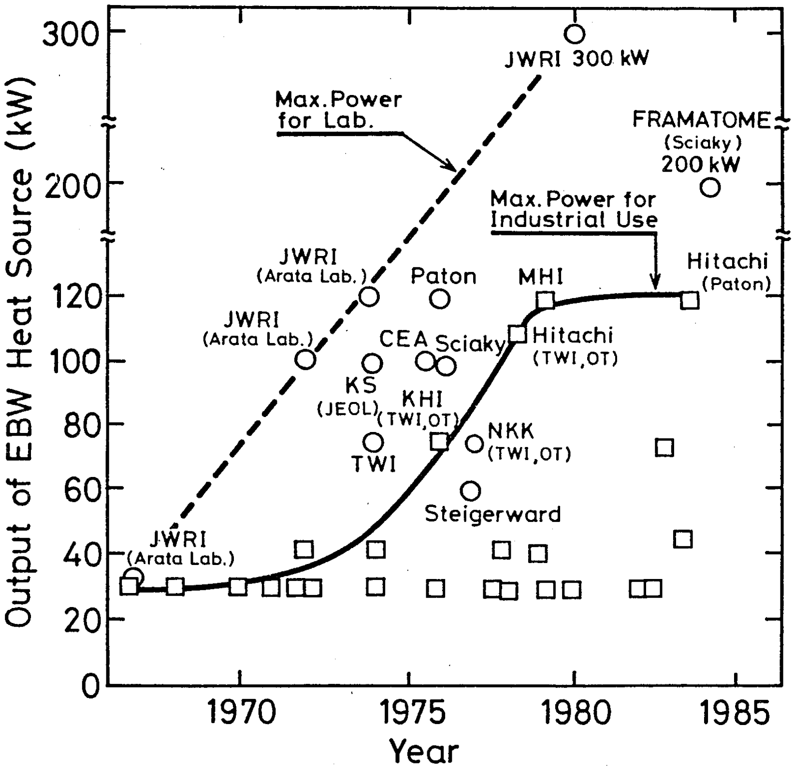



**Fig. 3** Ultra high energy density heat sources and their application.




o : Research
□ : Manufacturing

JWRI: Welding Research Institute, Osaka Univ.
KS: Kwasaki Steel Corporation
JEOL: Japan Electron Optics Laboratory Co., Ltd.
TWI: The Welding Institute, U.K.
KHI: Kawasaki Heavy Industries, Ltd.
CEA: Commissariat a l'Energie Atomique
NKK: Nippon Kokan K.K.
MHI: Mitsubishi Heavy Industries, Ltd. (Cooperate with Mitsubishi Electric Co., Ltd.)
OT: Osaka Transformer Co., Ltd.

**Fig. 4** Development of high power electron beams.

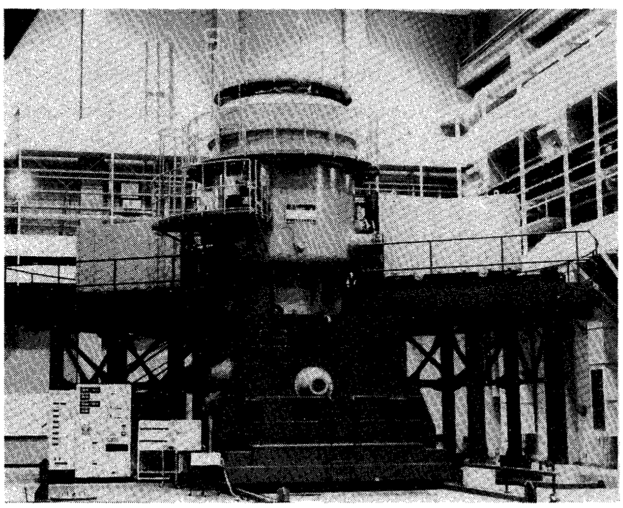


**Fig. 5** 300 kW electron beam welder.

A narrow heat affected zone (HAZ) is obtained, thus minimizing stress and maximizing weld precision. This result led to the practical industrial application of the system.

Certain weld defects characteristics of high energy density beams, including spiking, porosity, and cold shut, can be somewhat improved by oscillating the electron beam, but one attempt to find a more fundamental solution is the Tandem Electron Beam welding method[7] illustrated in **Fig. 9**. Various kinds of weld defects are likely to be created in high energy density beam welding by the reason of high energy density itself. This Tandem

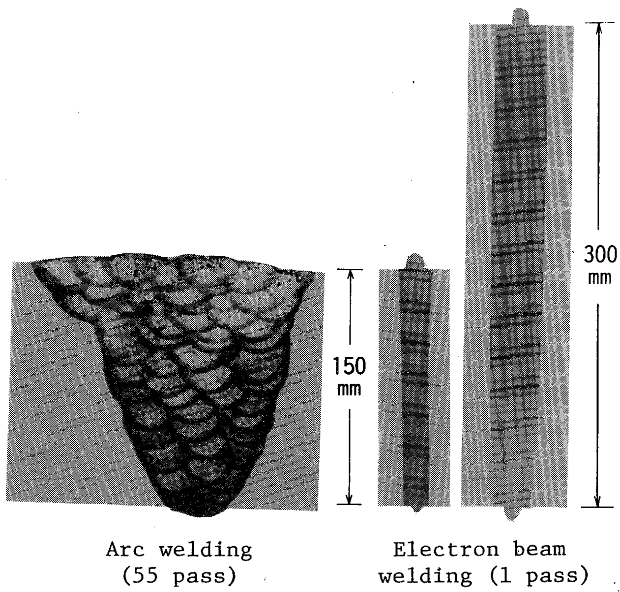



**Fig. 6** Comparison of bead cross sections between conventional welding and electron beam welding.

Electron Beam welding method combines two beams very skilfully as shown in Fig. 9 (a); the first beam offers the advantages characteristic of high energy density beams while the second beam works to correct or suppress the defects by the low energy density beam. Fig. 9 (b) and (c) show, examples of suppression of humping bead by this method. As the effectiveness of this welding machine has been confirmed at low output levels, the practicality of the machine shown in **Fig. 10** at medium output levels is

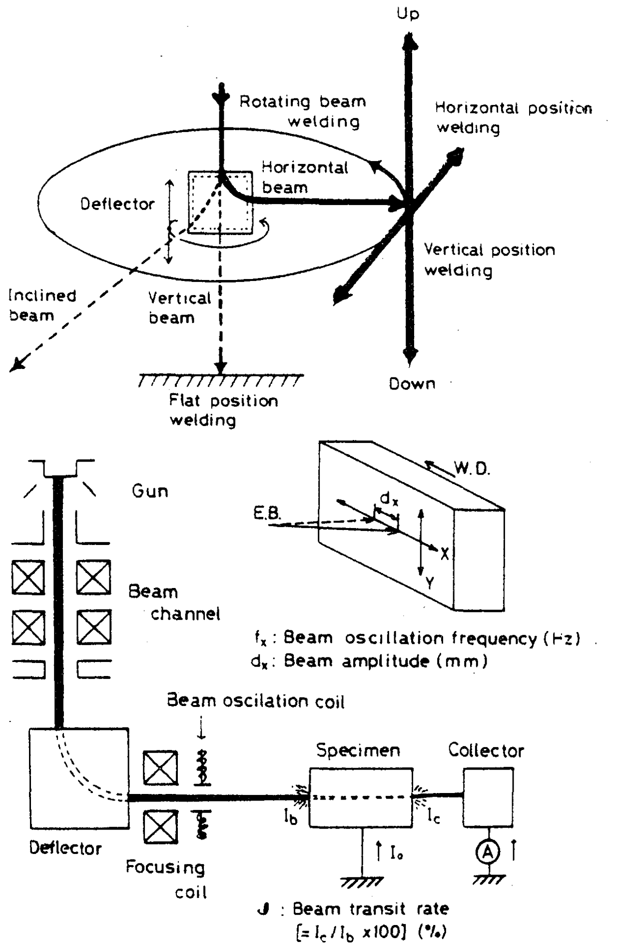



Fig. 7 All position electron beam welding method.

now under study.

As the electron gun always works in a vacuum, electron beam welding is also characterized by an absence of atmospheric influences. This characteristic, however, also brings many kinds of weld defects which are inherent to high energy density beams, and restricts the workability of process. Current research is attempting to resolve these shortcomings.

The vacuum welding chamber required in electron beam welding processes was thought during early developmental stages to offer significant advantages for welding reactive materials due to the clean atmosphere inherent in the vacuum chamber. But as attempts were made to utilize the deep penetration characteristic of this process in the manufacture of large structures, this apparent advantage became a major disadvantage. One attempt to solve this problem is the development of an electron beam welding machine in a low vacuum or a local vacuum.[8) **Figure 11** illustrates a local, low vacuum electron beam welding machine developed for welding 3.5 m O.D. SUS 304L toroidal vacuum chamber for nuclear fusion research. A local vacuum chamber composed of an inflation seal and lip seal maintaining a pressure of $10^{-2}$ Torr is moved for circumferential welding of the equatorial

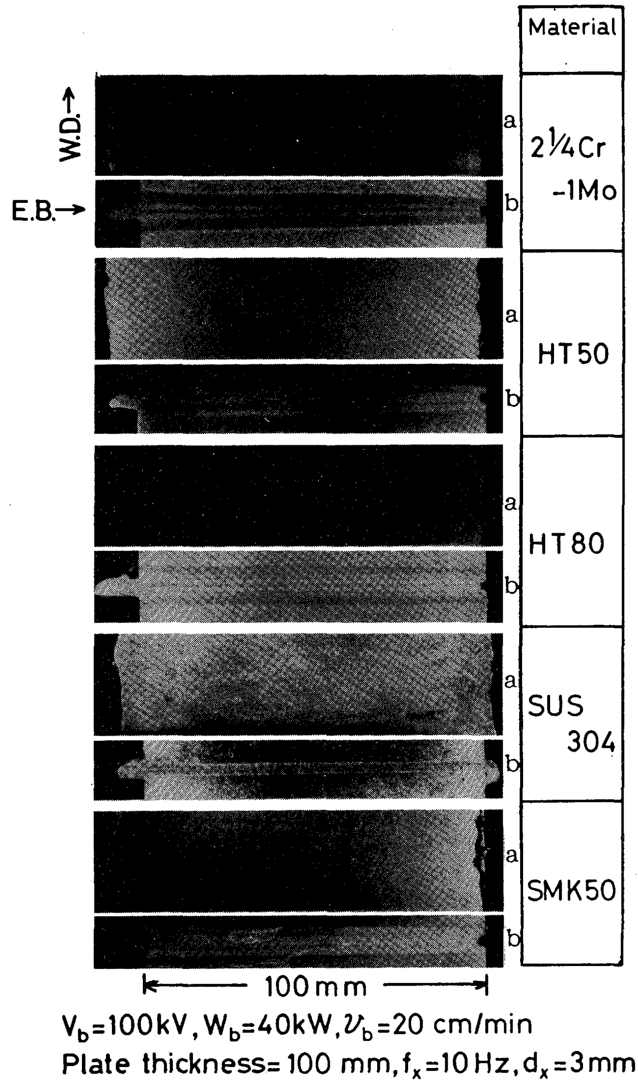
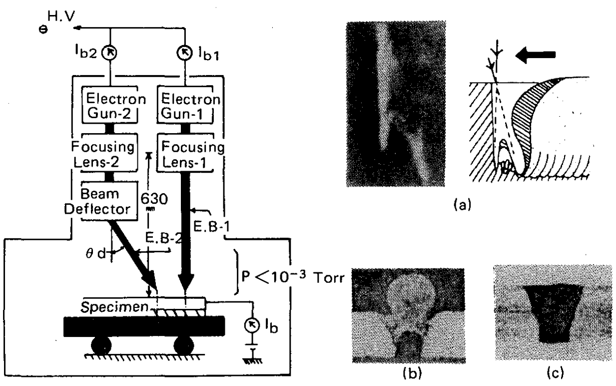



Fig. 8 Bead cross sections of various kinds of material welded by electron beam
a. Longitudinal b. Transvers




(a) Pinhole photograph and its explanation of beam hole X-ray
(b) Humping bead occurred in conventional high speed electron beam welding
(c) Sound bead obtaind by tandem electron beam welding

Fig. 9 Tandem electron beam welding.

joint. This system produces good welding results.

Electron beams can be finely focused in principle, and be easily controlled. In fact, low energy electron beams for diagnostic use have been applied under the highly

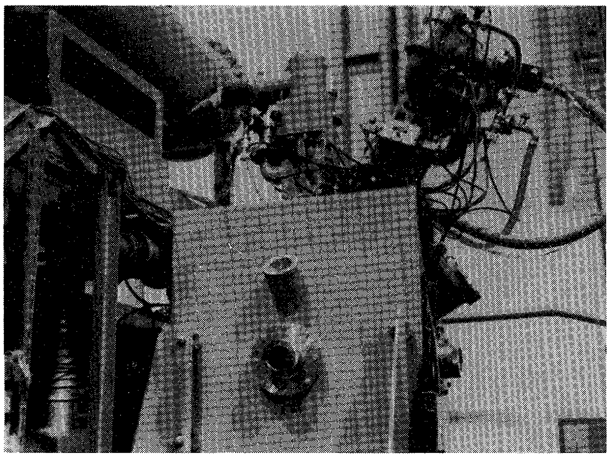


Fig. 10. 30 kW tandem electron beam welder.

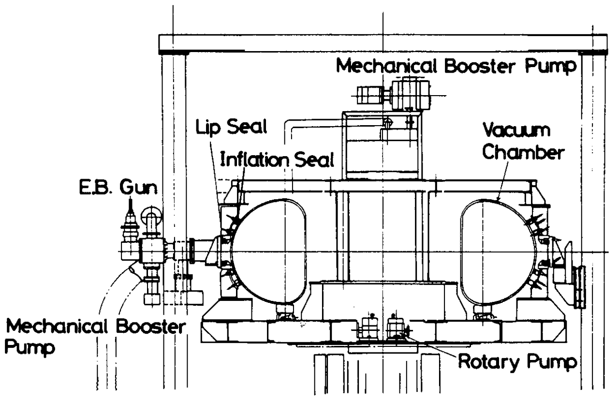



Fig. 11 Local vacuum electron beam welder.

regulated conditions. Recent advances in electronics and computer technologies have enabled even higher precision control of high output electron beams for welding. In addition, the combination of computers and sensors has also enabled automatic weld line detection and automatic work positioning,[9] as well as automatic focus detection.[10] **Figure 12** shows an on-line seam tracking system consisting of a computer and X-ray sensors; connecting this system with an NC table enables automatic welding of complicated welding lines.

### 2.2 Laser welding

Although the development of laser beams came later than electron beams, their relative ease of working and absence of vacuum working chamber requirements lead to rapid industrial application. At the same time, however, laser beams with high output and high quality assurance are difficult to produce. Recently numerous high output lasers in the 5 kW to 20 kW class have been developed and their welding applications are currently being investigated.

Practical high power $CO_2$ laser apparatus for industrial use was first provided by AVCO in 1970's as an commercially available 15 kW laser heat source, one of which was installed at JWRI as shown in **Fig. 13**. At present high output apparatuses over 10 kW are produced in many

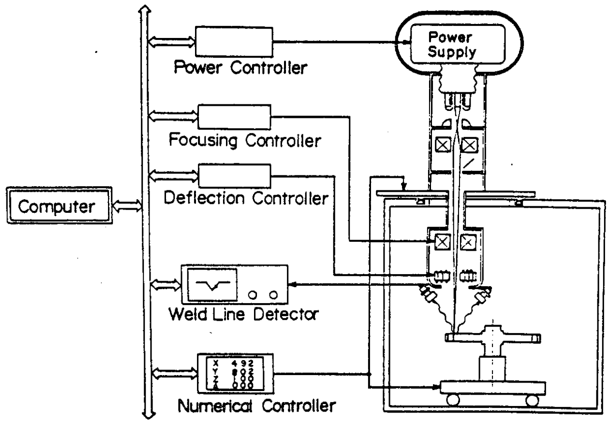



Fig. 12 Computer-controlled electron beam welder.

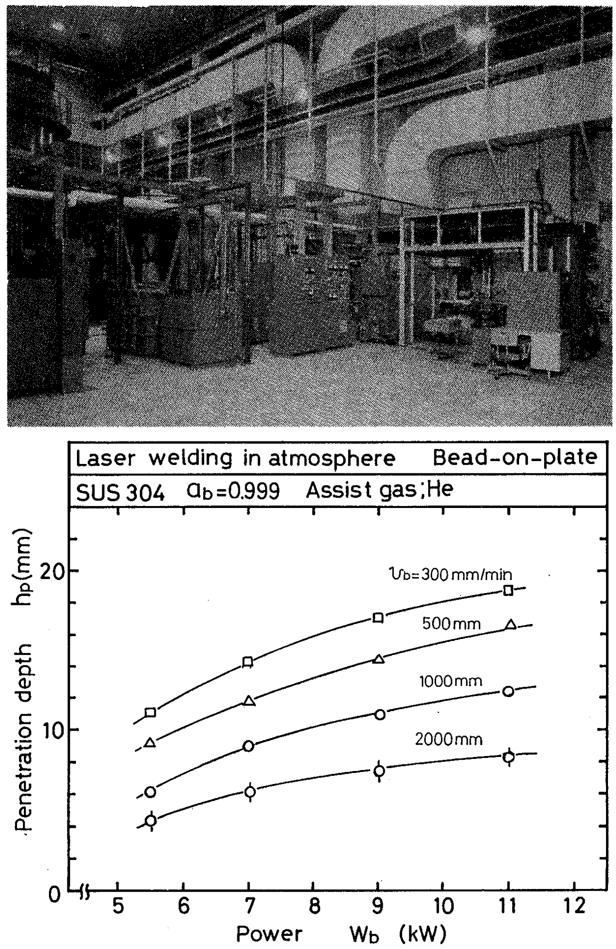



Fig. 13 15 kW $CO_2$ laser and its power characteristics.

countries. In the laboratory use a 25 kW-class apparatus has been developed[11] for a long time operation and a 100 kW-class one for a very short time operation. It should be emphasized, however, that a practical apparaturs for the present day industrial use with a high quality assurance is still within 10 kW class.

The greatest problem faced in welding with such high output $CO_2$ lasers is laser plasma. When high energy density beam welding is carried out in a normal atmosphere, high density, high temperature metallic vapour is greatly produced. The interaction of this metallic vapour with the laser beam creates so called laser plasma. This strongly absorbs or scatters the laser energy and prevents to obtain satisfactory weld beads.

Although an assist gas can be used to blow away the laser plasma, this gas also blows the molten metal. Strong jet of assist gas increases the size of the beam hole and prevents realization of a sufficient Wall Focusing Effect.[12)] Therefore, even when an assist gas is used, it is not so easy to obtain the penetration depth of more than 20 mm.[13)]

On the other hand, reducing the environmental pressure results in a reduction in plasma generation. **Figure 14** shows a quantitative comparison of penetration depth both in EB and laser beam welding. In both processes the penetration depth changes similarly with the ambient pressure. However, in case of EB welding the process is mainly governed by collisions with neutral and plasma particles and the total of these particle density in the beam pass directly affects the beam propagation and attenuates the beam energy before reaching to the materials and/or beam hole wall. While in case of laser welding only charged particle density, that is, plasma density dominantly affects beam decay. So that in EB welding the curve shifts to left side as the acceleration voltage is increased. While in laser process, it shifts to right side, if the plasma density is reduced, as we can find in the figure.

As the amount of plasma generated rapidly decreases at a pressure lower than several Torr, development and application of low vacuum laser welding method has been extensively studied by the author. This research effort seeks to improve laser welding performance without losing conventional laser functionability in low vacuum environment.

**Figure 15** illustrates systems of a partial and a high vacuum laser welding.[14)] The author named these new welding methods as "Vacuum Laser Welding". The high vacuum laser system can achieve a penetration depth of over 40 mm even in a 10 kW-class laser as shown in Fig. 15 (c), which is similar to that of electron beam welding.

In the partial vacuum welding system, a dynamic window replaces the conventional ZnSe or KCl lens, thus enables one to introduce a high output laser beam into the vacuum. This system achieves a penetration depth of over 25 mm even in a low vacuum of 50 Torr.

As use of a low vacuum or local vacuum reduces laser operability, other investigations have sought to improve welding performance in a normal atmospheric environment. One of these techniques is called LSSW (Laser Spike Seam Welding).[15)] This method focuses on the delay between laser emission and laser plasma generation. The laser is concentrated on the same weld point and shifted forward the moment before production of laser plasma increases, by which the laser energy is used very effectively to attain a deep penetration. As shown in **Fig. 16**, this method offers better weld penetration than conventional techniques at the same power and welding speed.

In another attempt to improve weldability, a gap at the weld point is opened before welding begins, and the gap is filled with a filler wire to enable welding of thick plates.[16)] This system is illustrated in **Fig. 17**. This technique also increases the allowable butt gap error, and is being considered as one means of compensating for the lack of high precision characteristics in laser welding system.

As beam output increases so does the effect of the laser

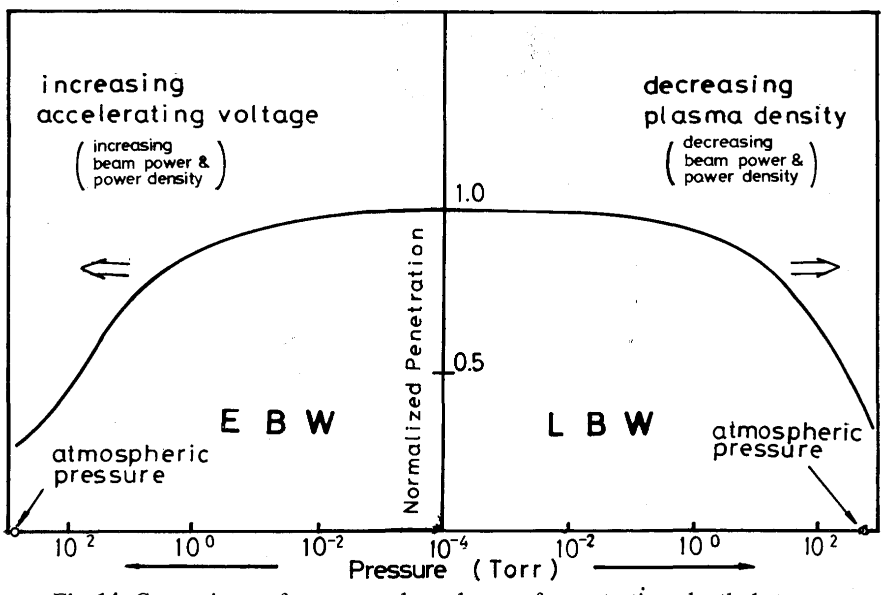



**Fig. 14** Comparison of pressure dependence of penetration depth between electron and laser beam welding.

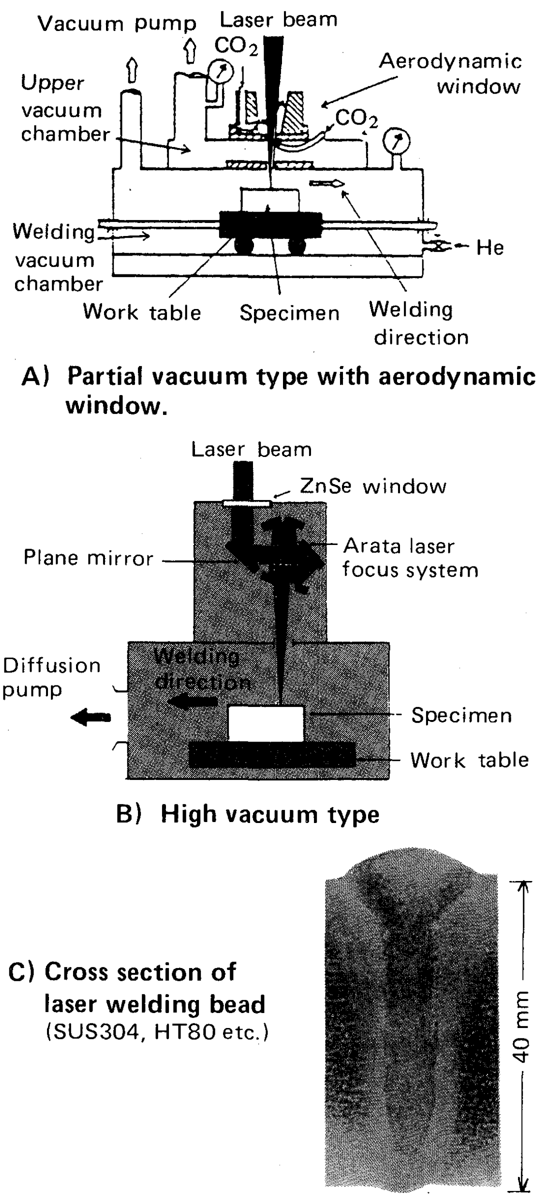



Fig. 15 Experimental apparatus of vacuum laser welding.

beam focusing system on beam characteristics and welding characteristics. Three conventional system are shown in Fig. 18 (a), (b), (c); in (a) the heat input to lens is incompatible with high output, and large aberrations in (b) and (c) result in poor focusing efficiency. In contrast, however the effectiveness of "Arata Laser Focusing System"[17] shown in (d), (e), and (f) increases with the laser output. Though these three systems are designed with the same principle, system (d) is used for cylindrical beam, and (e) and (f) for coaxial one. System (f) is particularly effective with high output annular beams widely employed in multi-kilowatt lasers.

### 2.3 High energy density beam gas cutting

High energy density beams like EB and laser can be used also for a precise cutting as well as welding process.

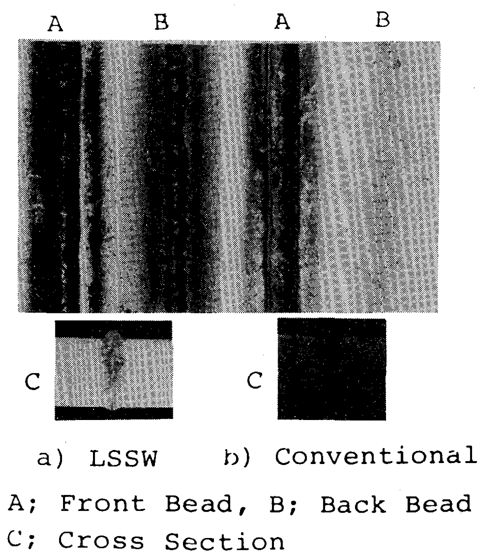



Fig. 16 Comparison of bead cross section between LSSW method and conventional method.

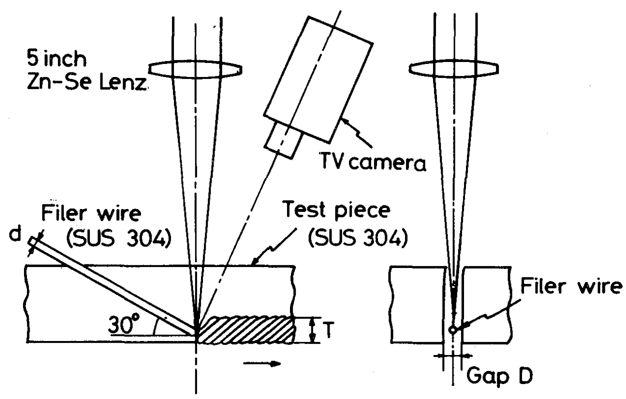



Fig. 17 Laser welding with filler wire.

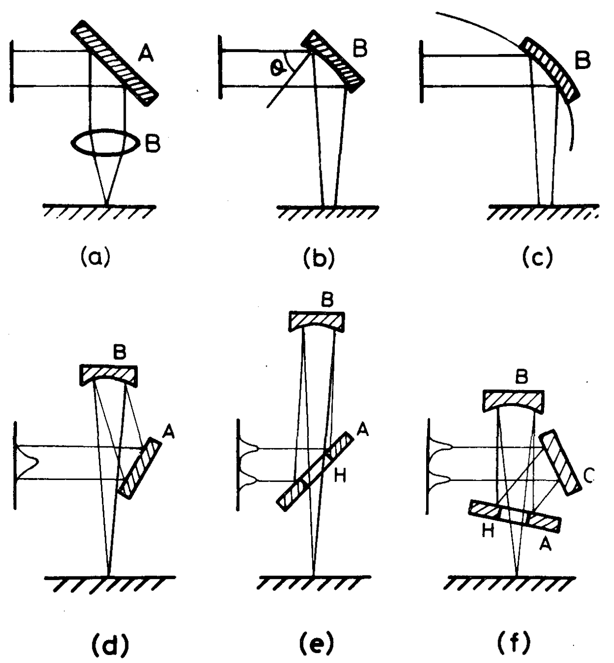



Fig. 18 Arata Laser Focus System.

In regard to electron beam, in the early time before the development of EB welding Steigerwald et al. have studied around 1950 piercing, drilling and cutting in a vacuum environment, though the output was very low. While the author has considered to apply EB and laser to cutting at an atmospheric pressure and in 1966 succeeded[18] in making a cooperative use of gas dynamic pressure and/or gas reaction energy with these beams and named them as "EB Gas Cutting" and "Laser Gas Cutting", respectively. By these methods the author has obtained good results in the cutting of various metals and ceramics.[19,20] As is well known the laser gas cutting are more frequently applied presently and the EB gas cutting has been studied for the cutting of rocks[21,22] rather than metals. In the laser gas cutting superior cutting results of a thick plate has been obtained recently by the development and use of plural nozzles.[23,24]

**Figure 19** shows typical example of high energy density beam gas cutting by EB and laser heat sources in open air, which has been developed by the author for the first in the world. On the right is shown laser gas cutting and on the left EB gas cutting. They give a similar cutting results as is shown in the lower part of the figure. These high quality cutting are obtained for various metal and non-metal plates.

### 2.4 Plasma beams

Plasma beams, one of high energy density beams, were developed as plasma jets. Today plasma beams are used with a variety of engineering applications, including melting of metallic materials, processing (cutting, welding, thermal spraying), and high temperature chemical reactions. The outstanding operation, low heat generation costs, high output, high temperature, and high heat efficiency of plasma jets indicates an expanding range of applications in the future. However, a conventional plasma jet has a drooping voltage-current characteristics while leads to the necessity of considerably large current to obtain a high output as shown in **Fig. 20**. This causes the errosion of electrode and other problems inhibit high output designs, and most plasma jets in use today feature output levels below 100 kW.

To overcome these problems, a gas tunnel type high power plasma jet system in which the plasma beam is generated through a gas tunnel applying a powerful thermal pinch effect was developed for generation of high temperature, high energy density, high output plasma jets.[25]

**Figure 21** shows a simple connection of the conventional and the gas tunnel type plasma jet, and also the difference in the pressure distributions[26] between conventional type and gas tunnel type plasma jets. Output levels over 400 kW have been obtained with the experimental device shown in Fig. 20. In the figure is also shown a comparison of their characteristics. Use of a special high speed vortex protects the electrodes, and the thermal pinch effect constricts the plasma jet, and suppresses the heat load on the torch walls. This system easily achieves high output levels with a stable plasma jet for high performance fusion of high melting point alloys, fusion of high melting point insulators such as ceramics, and metal refining.

Applications for materials processing, surface treatment, and thermal spraying with high melting point

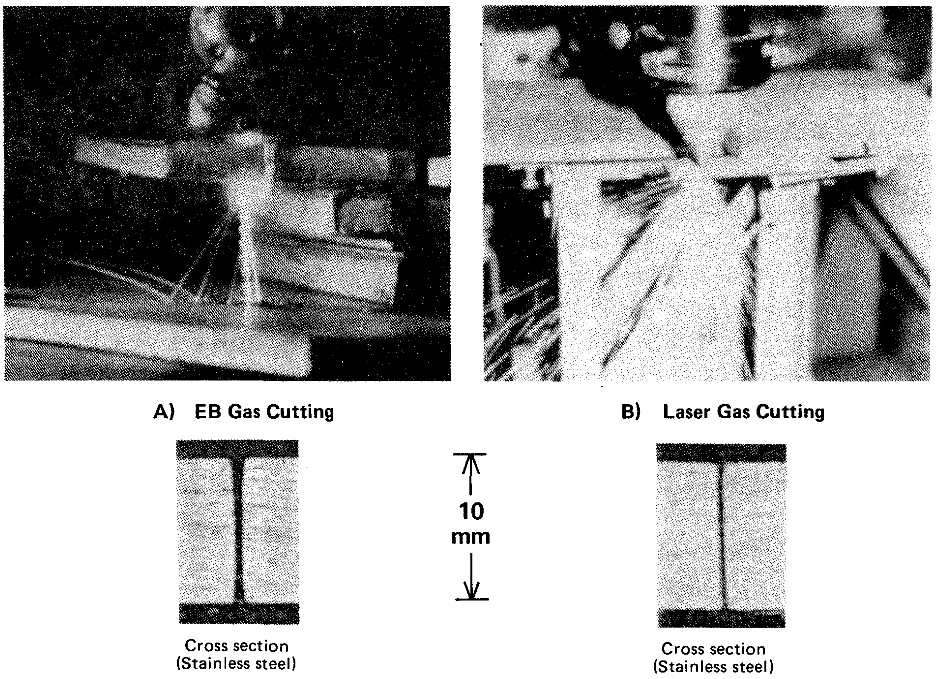
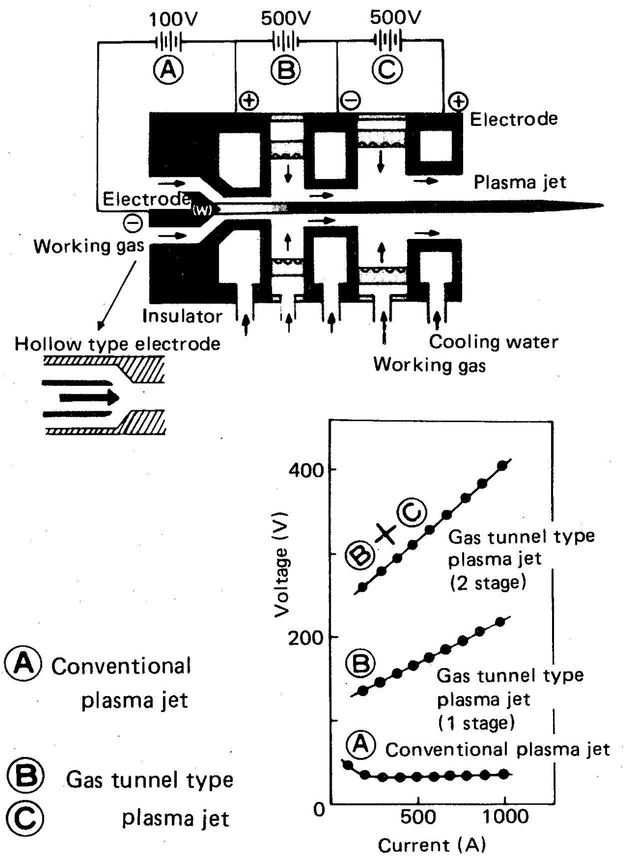



**Fig. 19** High energy density beam gas cutting.




| | High power plasma jet | Conventional plasma jet |
|---|---|---|
| Electrical potential difference | 40～50V/cm | 10～20V/cm |
| Output | 200kW | <100kW |
| Plasma temperature | 20000 K | 10000 K |
| Thermal efficiency | 80% | 50% |

**Fig. 20** Gas tunnel type plasma jet and comparison with conventional type plasma jet.

metallic materials, non-metallic materials and ceramics should bring future improvements in quality and efficiency. Other potential applications utilizing the high temperature characteristics of plasma jets include high temperature reaction production of compounds and crystals, production of high purity, spherical alumina powder, and destruction of toxic substance.

### 2.5 Industrial application of high energy density beams to manufacturing

**Figure 22** shows a vacuum chamber manufactured by electron beam welding method for nuclear fusion research[2]. This structure has a very complex helical configuration and needs precise processing. It is impossible to produce such a chamber by arc welding method. The major radius of the chamber is 2.2 m. The chamber has

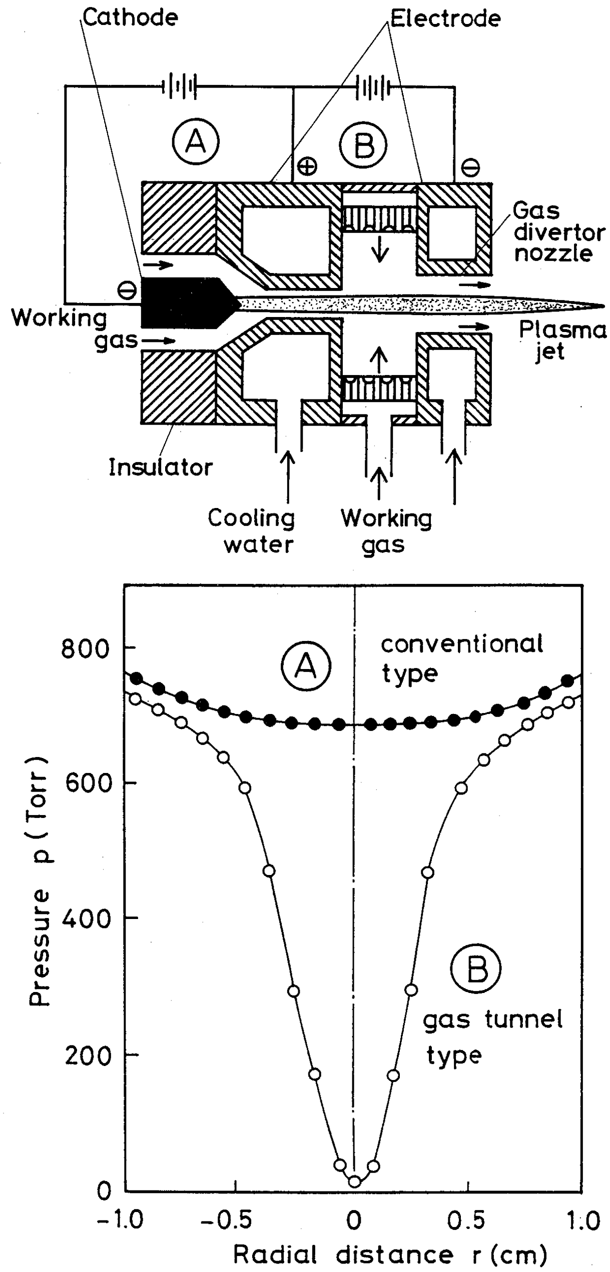



**Fig. 21** Gas tunnel type plasma jet and its radial pressure distribution.

two parts of thickness with 20 and 33 mm.

**Figure 23** shows pressure vessels of 6000 m class deep-see exploration space vehicle also produced by electron beam welding.[2] Development are progressing for these two kinds of materials shown as examples.

**Figure 24** shows an example of nuclear reactor pressure vessel of stainless steel.[2] The diameter is 3 m and the height is 5 m. Thickness is 40 mm.

## 3. Robotics in Welding and Cutting

High performance and high precision process control are required to assure consistent quality in weld joints and welded structures produced with arc and/or high energy

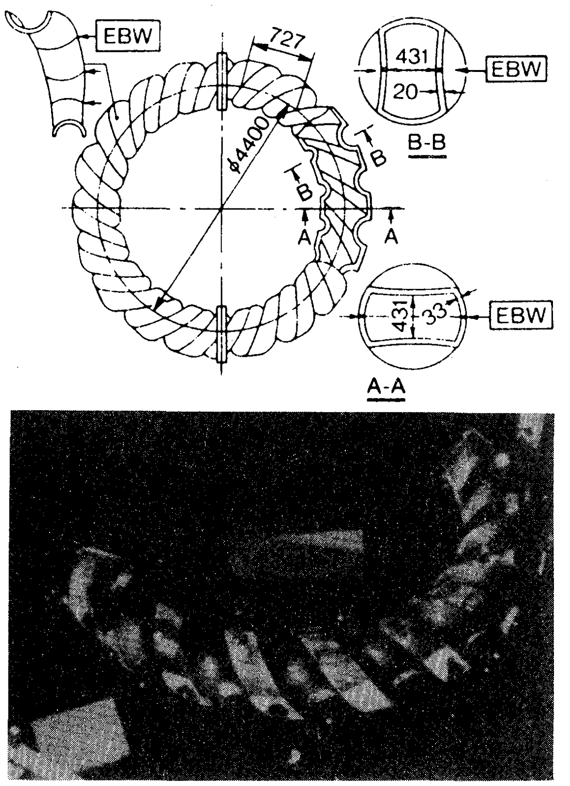
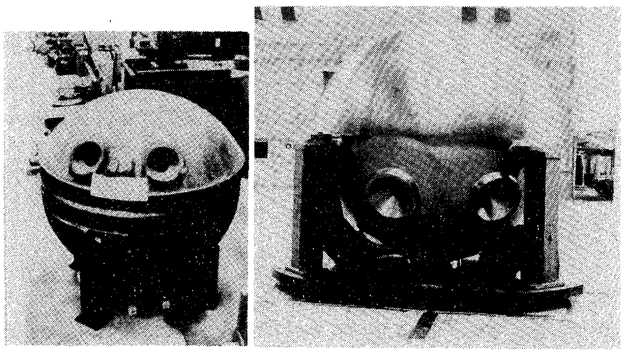



Fig. 22 Vacuum chamber for nuclear fusion research.



(a) (b)

Fig. 23 Vesseles for deep-sea exploration space vehicle.
(a) 10Ni-8Co,
Diameter: 2100 mm, Thickness: 80 mm
(b) Ti-6Al-4V,
Diameter: 2000 mm, Thickness: 80 mm

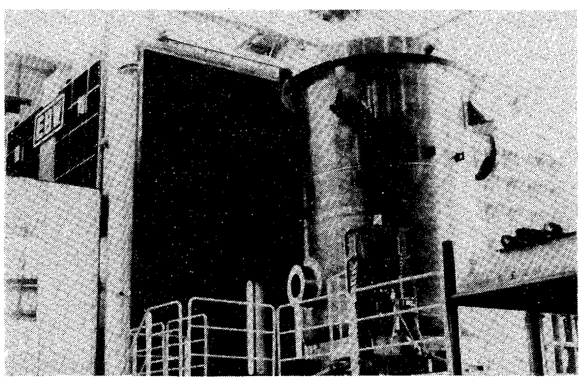



Fig. 24 Pressure Vessel for Nuclear Reactor.
(AISI 304, Diameter: 3000 mm,
Height: 5000 mm, Thickness: 40 mm)

density beam processes. Robots have rapidly developed and been applied in a wide range of manufacturing fields in recent years to meet these requirements.

The arc welding robot is the most common industrial robot today, and in this section will be examined the current state of welding robot production and use. **Figure 25** shows welding robot manufacturing trends in Japan.[27] As the chart indicates, arc robot manufacture increased dramatically through 1982, aided by severe price competition and reaching market saturation in 1983. Furthermore, while most arc welding robots are self-standing devices, they are increasingly used as part of larger welding and manufacturing system,[28] whose example is illustrated in **Fig. 26** as the automobile chassis and frame welding line.

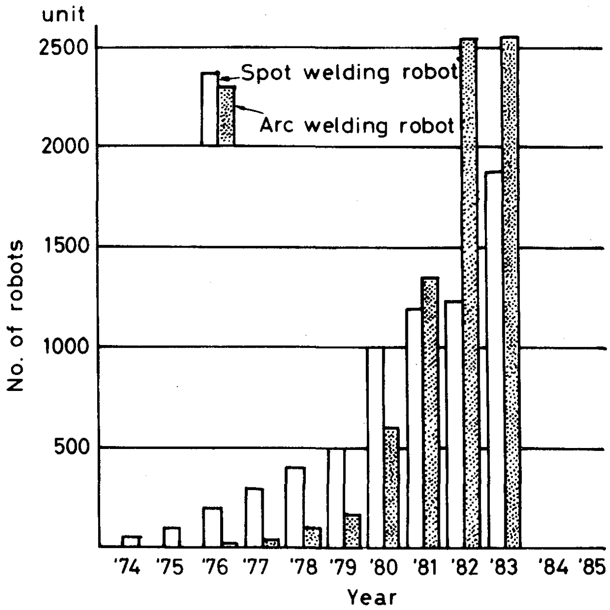



Fig. 25 Trend of production of welding robots in Japan.

Teaching an arc welding robot is a complicated process, and the time required for robot teaching is one of the biggest roadblocks to greater use. The development of advanced sensors is expected to reduce robot teaching time requirements, simplify the procedure, and expand the range of robot applications.

Functions required of arc welding robot sensors include the ability to; (i) recognize the workpiece and those spots requiring welding; (ii) properly and accurately trace the welding seam even under a variety of poor welding conditions; (iii) detect the shape and gap of the joint, determine and compensate for any variance with the specifications; (iv) detect and prevent any interference and obstruction of foreign objects with the torch or robot arm; (v) detect weld quality during the welding process and to adjust the welding conditions when necessary; (vi) automatically conduct a nondestructive examination of the welding joint upon completion of the welding procedure.

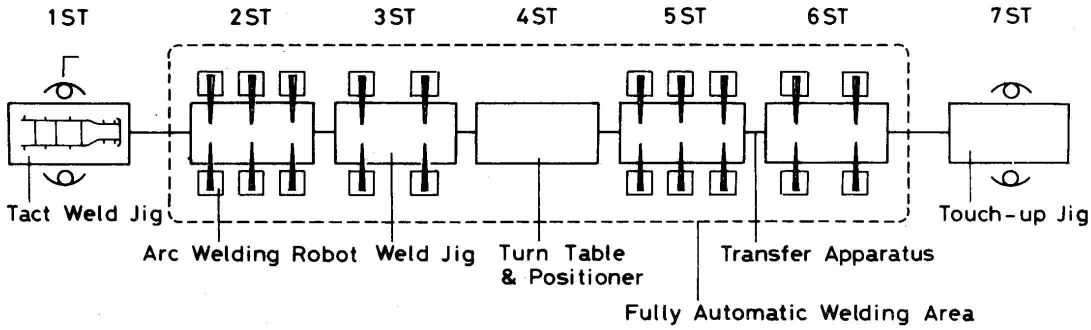



Fig. 26 Welding line for automobile chassis and frame.

Of these various functions, there currently exist only sensors to detect the beginning and end of the workpiece in (i), and arc sensors and optoelectronic sensors in (ii). All others are still in the experimental stages of development. New sensor types, high performance processors for sensor output processing, and cost reductions are current research and development objectives. Other research topics include the application of arc welding robots in the manufacture of such large structures as ships and ferro-concrete bridges. New actuator designs and the development of light-weight, portable robots are being examined[29] to solve these problems whose example is shown in **Fig. 27**.

With the development of CAD systems, the desire to input CAD system output directly into the welding robot has naturally risen. While this requires equipping the robot with a language processing capability and standardizing the programming language. It also requires standardization of both robot software and CAD system disk operating systems (DOS). The diversification of microprocessors and the development of CAD systems for microcomputers increases the possibility such common operating systems as CP/M, MS-DOS, and UNIX will be enhanced with a real-time function and employed in robot operating system. Low software productivity is a problem not only for industrial robots, but for all computer-related technologies and, therefore, all industrial technologies.

**Figure 28** shows typical examples of robots used today for, respectively, arc welding, cutting, and flame spraying. **Figure 29** shows a robot[30] developed very recent for

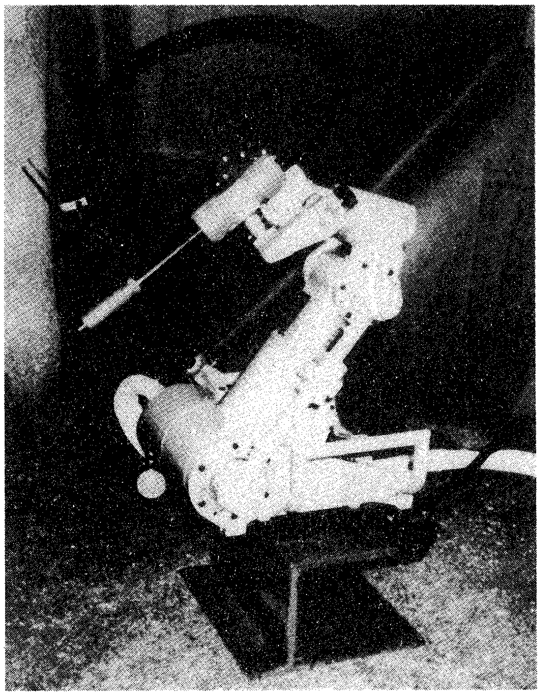


Fig. 27 Portable robot for shipbuilding.

automation of welding line of steel plate factories. **Figure 30** shows a three-dimensional laser welding and cutting robot[31] developed to automate high energy density laser beam welding and cutting processes. This system uses a 500 W $CO_2$ laser and robot functions include five-axis, fully integrated drive system. For instance, specification of the plate thickness and cutting speed enables the control system to automatically set optimum laser cutting

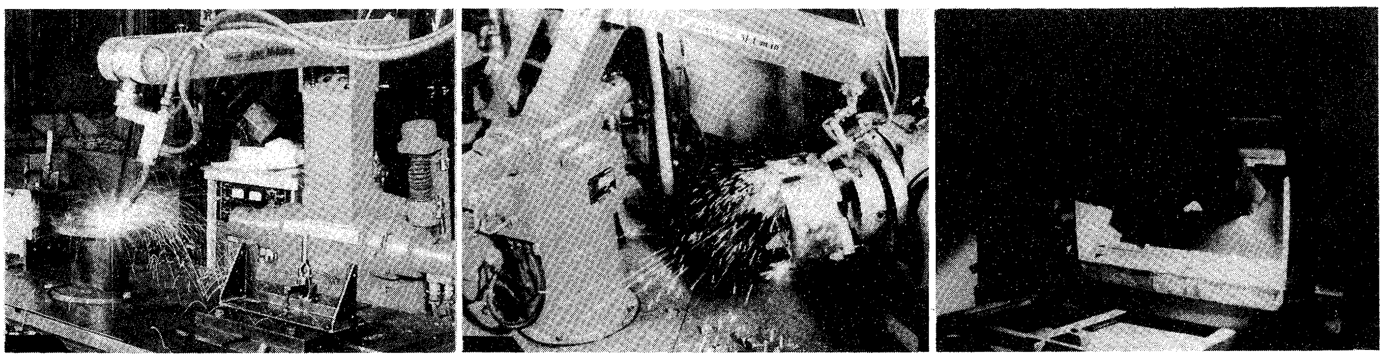


Fig. 28 Typical welding robots for arc welding, cutting and flame spraying.

conditions.

It is most likely that future robots will gradually grow away from teaching-playback control systems to intelligent robots offering automatic control and detection capabilities. Reasons behind these probable developments are a lack of skilled technicians and extreme diversity of welding processes and environments. Increased use of intelligent robots will promote factory automation and thereby effect other changes in the factory.

An Artificial Intelligence (AI) system consists of knowledge base and inference mechanism or inference engine as shown in **Fig. 31**. What should be remarked in Artificial Intelligence is its inference mechanism. A computer infers based on pieces of causalities by communicating with the user. By the conventional method shown below we have to formulate or develop a particular program for a particular condition. While by AI technique, we do not have to prearrange the piece of causalities in order to solve the problem, because the computer infers and picks up the appropriate pieces of causalities to solve the problem.

What is more important is that we can know what is lacking in the knowledge base by communicating with the computer and we can add new pieces of information to the knowledge base.

On the basis of these considerations, an EXPERT system using PROLOG and capable of determining welding conditions for pressure vessels has been developed[32] at Osaka University. This system uses experience to com-

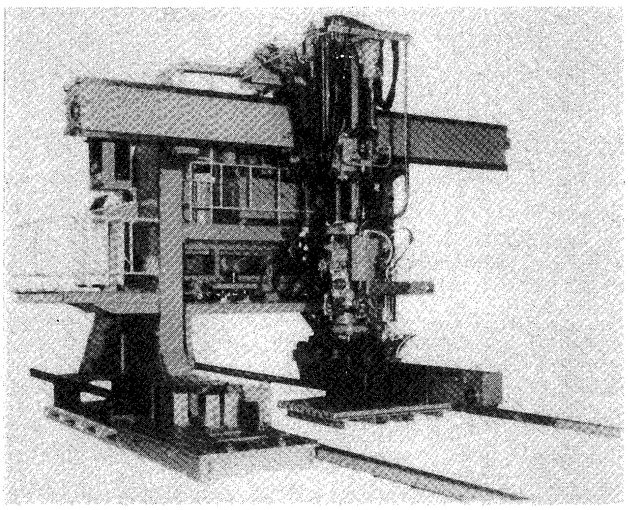


**Fig. 29** Robot for automation of welding line of steel plate factories.

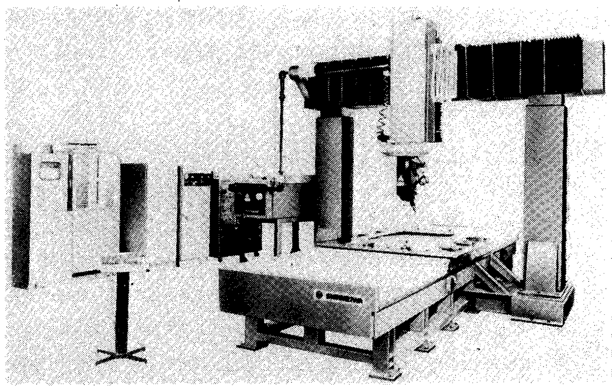


**Fig. 30** Three-dimentional laser welding and cutting robot.

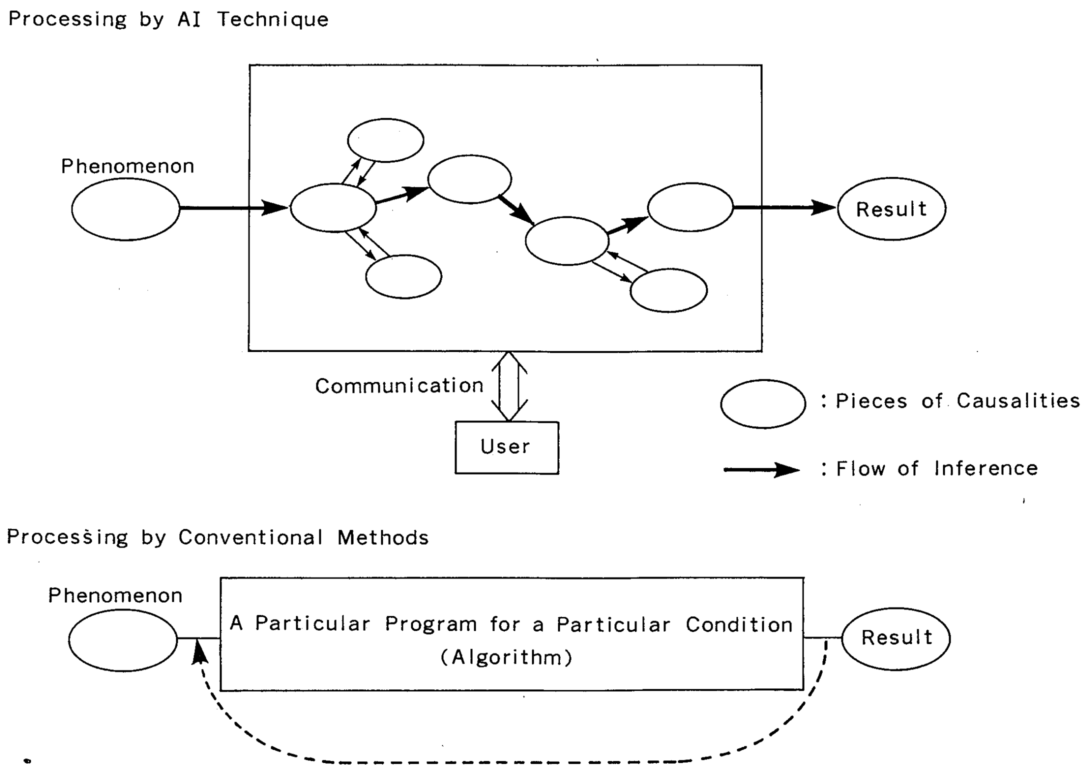



**Fig. 31** Artificial intelligence and conventional algorithm.

pensate even for deviations in conditions requiring manual input by conventional algorithmic techniques.

The ability for tomorrow's intelligent robots to handle standard conditions alone will not be enough. They will need to be able two work under an extremely wide range of conditions. Accordingly, it is equally important to develop intelligent robots utilizing artificial intelligence technologies.

## 4. Surface Modification by High Energy Density Beams

As already mentioned high energy density beams offer good operability enabling precision control of heat input and its density in wide ranges. Furthermore, these beams can apply a large heat input in a short time, and are used as the heat source not only for welding, but in a number of different surface modification processes. This section will consider primarily laser beam applications.

### 4.1 Laser gas hardening

A surface hardening technique in which titanium is irradiated with laser in a nitrogen atmosphere to form a TiN layer or Ti layer containing a high concentration of nitrogen at or directly below the fusion surface is being studied.[33] This technique employs the gas-liquid reaction occurring at high temperatures and is characterized by the direct formation of a ceramic coating on the base material.

**Figure 32** shows a comparison of hardness distribution

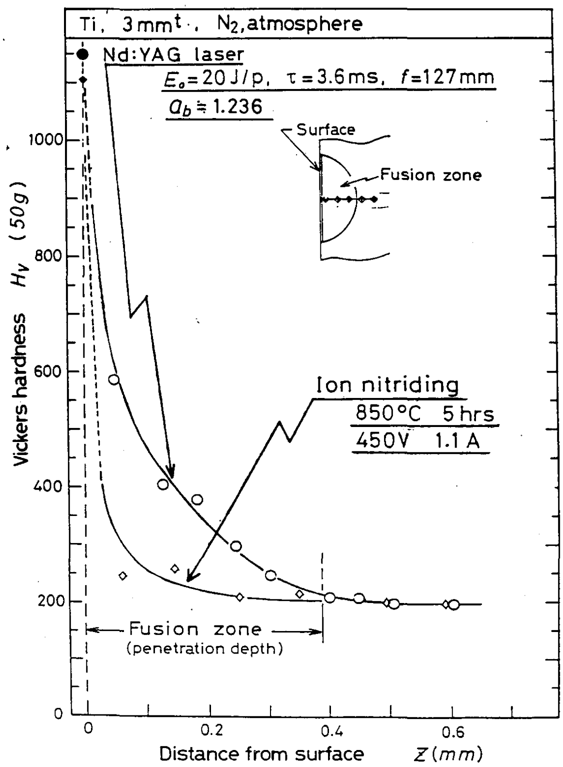



Fig. 32 Comparison between laser gas hardening and ion nitriding method.

between laser gas hardening and conventional ion nitriding method. Laser gas hardening can harden titanium surface more rapidly and deeply than conventional method.[34]

**Figure 33** shows the relationship between the pressure of the nitrogen atmosphere and Vickers hardness, and between nitrogen pressure and TiN layer thickness. As these indicate, the higher the nitrogen atmosphere pressure, the thicker and harder the TiN layer.

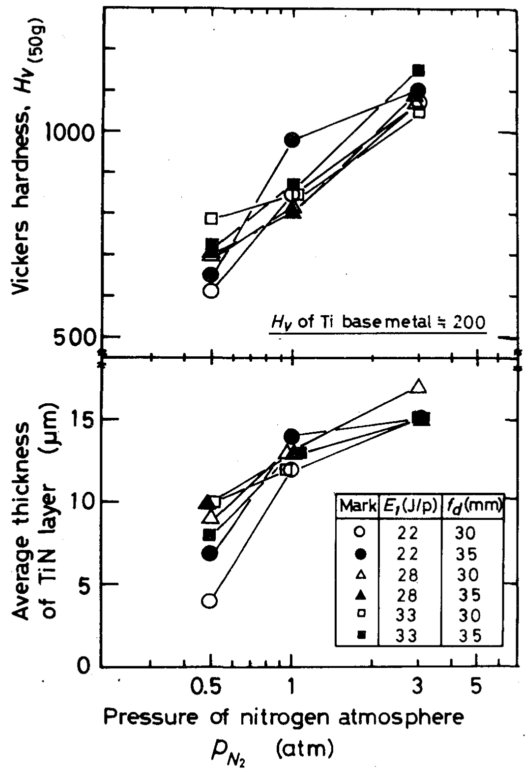



Fig. 33 Average thickness of TiN layer and Vickers hardness.

### 4.2 Laser alloying

In subsequent studies, the surface of several materials (mild steel, SUS 304, nickel, copper, and aluminum) were coated with an acrylic solution containing titanium powder. The surface was then irradiated in a nitrogen atmosphere with a pulse Nd: YAG laser (35J/pulse, 30 mm defocus distance) to form a TiN alloy and harden the surface.[35] As the results shown in **Table 1** indicate, the irradiated surface was harder in each case than the base material, clearly demonstrating the ability to form a TiN alloy and harden the surface of the base material by coating the surface with titanium powder and irradiating this with a laser.

**Figure 34** shows the results of hardness and titanium content tests in which an alloy of SUS 304 and titanium was irradiated by a laser in a nitrogen atmosphere. At titanium concentrations over 10% the surface appeared gold and at over 30%, hardness of Hv = 730 – 970 was

**Table 1** Increment of surface hardness for several materials.

| Materials | Vickers hardness, Hv (50g) | | |
|---|---|---|---|
| | $(Hv)_s^*$ | $(Hv)_b^{**}$ | $(Hv)_s/(Hv)_b$ |
| Mild steel | 800<br>650–930 | 130 | 6.2 |
| AISI 304 | 830<br>800–870 | 200 | 4.2 |
| Nickel | 650<br>580–760 | 110 | 5.9 |
| Copper | 740<br>630–810 | 85 | 8.7 |
| Aluminum | 580<br>500–650 | 45 | 13 |

* : Hardness of treated surface
**: Hardness of base metal

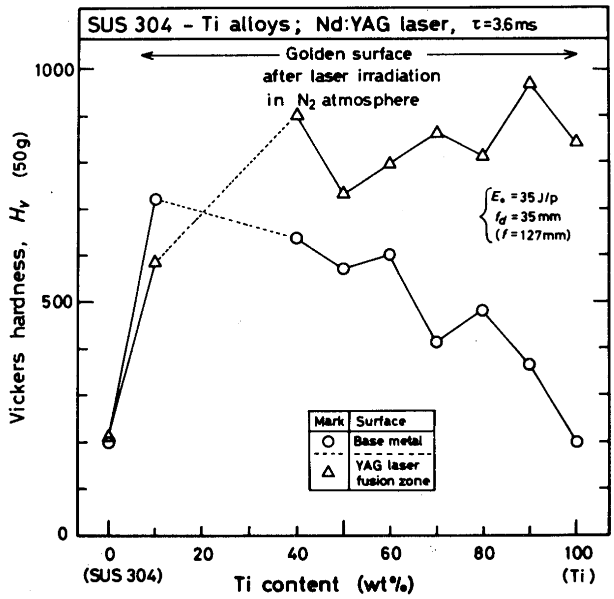



**Fig. 34** Vickers hardness of SUS 304-Ti alloys.

obtained. In identical tests conducted with an aluminum-titanium alloy, however, virtually no change was observed until the titanium content exceeded 50%. While laser irradiation produced a TiN layer with increased hardness on the surfaces of each test sample, the effectiveness of the process varied with different materials.

### 4.3 Laser solution treatment

HAZ sensitization in SUS 304 arising from the thermal history during extended use and from the welding heat cycle is the cause of integranular stress corrosion cracking (IGSCC) and intergranular corrosion. Conventional preventive techniques include the use of low carbon steel or stable steels containing TiNb, stabilization heat treatment during the low weld heat gain stages or at 800° to 900°C after welding, or solution heat treatment at 1050° to 1100°C.

While solution heat treatment is extremely effective, it is not generally suitable with large structures due to problems with heat deformation and cooling speed arising from the high temperatures used. On the other hand, anticorrosion considerations do not require heating of the entire structure, and by using local processes which achieve sufficiently high cooling speeds by heating only the surface, solution heat treatment processes can also be used with large structures. Techniques to improve the corrosion resistance of sensitized stainless steel using local solution heat treatment processes and a laser beam heat source are also being considered.[36] **Figure 35** shows a cross section perpendicular to the bead following laser irradiation (1 kW beam output, 7 mm beam diameter, 1 m/sec) of the HAZ sensitized area of S-2 steel, TIG-Welded with a 10 kJ/cm heat input. Laser irradiation changed a ditch structure of 0.3 mm deep in the HAZ sensitized area into a step structure, indicating densensitization of the area. Furthermore, as shown in **Table 2**, laser irradiation completely desensitized other HAZ areas 0.2 to 0.4 mm from the surface.

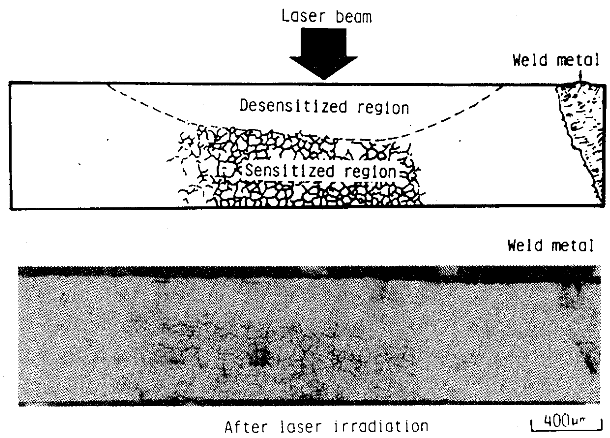



**Fig. 35** Structure of bead after laser irradiation.

**Table 2** Laser irradiation conditions of desensitization treatment.

| Heat input (kJ/cm) | Laser power (kW) | Beam traveling velocity (m/min) | Beam diameter (mm) | Result |
|---|---|---|---|---|
| 10 | 1.0 | 1.0 | 7 | Desensitized |
| | 1.5 | 2.0 | 7 | Desensitized |
| 20 | 1.0 | 1.0 | 7 | Desensitized |
| | 1.5 | 2.0 | 7, | Desensitized |

### 4.4 Laser surface fusion treatment

Other studies have examined techniques to improve the oxidation resistance by modifying the composition and structure of alloy layers by surface fusion with a laser. **Figure 36** shows the results[37] of oxidation resistance tests conducted after a 1.7 to 2 kW $CO_2$ laser (1 to 4 mm beam diameter) scanned the surface of SUS 430 and

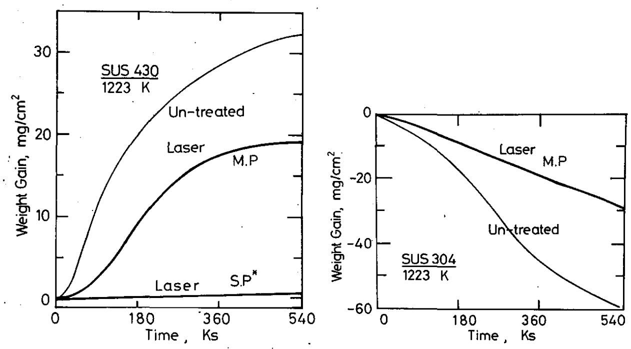



**Fig. 36** Weight increment of SUS 430 and SUS 304 treated by laser.

SUS 304 either once or multiple times at 0.3 – 0.5/min. Oxidation resistance was determined by the amount of weight gain and spalling of scale on SUS 430 and SUS 304, respectively. The oxidation resistance of both SUS 430 and SUS 304 was determined to have improved from laser fusion. XMA analysis and X-ray diffraction showed that the oxide layer of laser-irradiated materials has an extremely high chromium and silicon concentration, and that there are large amounts of $Cr_2O_3$ and $SiO_2$ in the film. It is believed that for the microstructural changes caused by laser irradiation to improve oxidation resistance, chromium and silicon are first dispersed over the surface, thus forming a protective layer.

### 4.5 Laser thermal spraying

A laser beam can also be easily applied to the thermal spraying of metals and ceramics, in competition with the conventional methods using plasma jet, gas flame and so on. This method is known as "Laser Thermal Spraying". Characterized by the high energy density of the laser heat source, the spraying material is easily heated to a high temperature and can be melted effectively.

**Figure 37** shows a photograph of the laser thermal spraying at operation.[38] The wire supplied is heated and melted near the focusing point of the laser at the spraying nozzle exit and the melted drops are blown by assist gas to the surface of a test piece. Thickness of coating film can be controlled easily by changing the experimental conditions such as speed of wire supply and traverse of test piece. The most important factor governing the utility of this method is how to powderize the wire as quickly as possible.

Moreover, if reactant gas ($O_2$, $N_2$, ...) is used as the assist gas, material coating such as $TiO_2$, TiN and other non-metalized coating can be obtained. **Figure 38** shows an example of the cross-section of TiN coating[38] obtained with this method and the structure is similar to that by other spraying methods.

In the laser thermal spraying, powders as well as wires can be used as spraying materials which are metal and/or non-metal. Moreover thermal surface treatment of the coating by various methods is also possible by using a laser, which will become more important in near future.

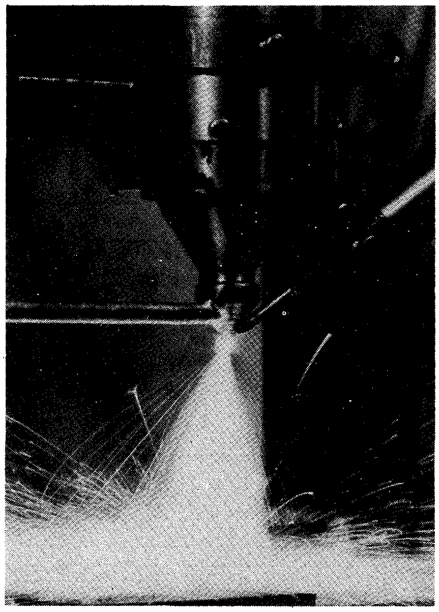


**Fig. 37** Laser thermal spraying.

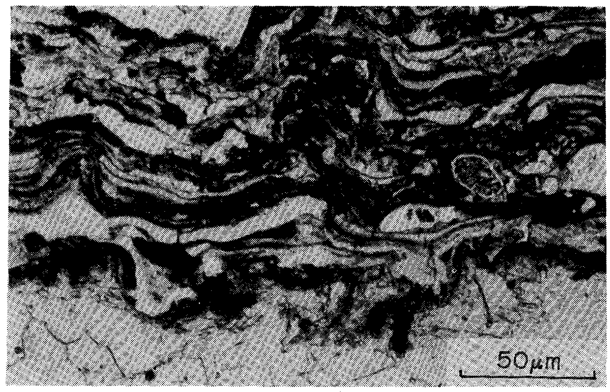



**Fig. 38** Cross-section of TiN coating.

## 5. Production of Composite Materials by Modified Conventional Methods

Rapid development in the space, atomic power, and electronics industries in recent years have created new and demanding materials requirements. Furthermore, conventional metallic and organic materials are frequently incapable of withstanding these new conditions. On the other hand, new ceramics (nonmetallic inorganic materials) exhibit superior heat resistance, corrosion resistance, high temperature oxidation resistance, and wear resistance, and are thought to offer the performance required in many new industrial applications.

Current ceramic compounds, however, suffer from some shortcomings (e.g. poor machinability, low resistance to thermal shock, manufacturing problems faced in the production of large and complicated structures), and their use is therefore limited. Developments in the composite materials field have come from efforts to compensate for deficiencies in ceramics, metallic materials, and plastics by composing two or of these more materials into a new material offering improved performance and new functions.

The bonds between the component materials are particularly important when manufacturing new composites. Conventional welding techniques, including brazing and diffusion welding, have been modified and effectively utilized in composite material manufacture. New heat sources, e.g. plasma beams and laser beams, are also being considered.

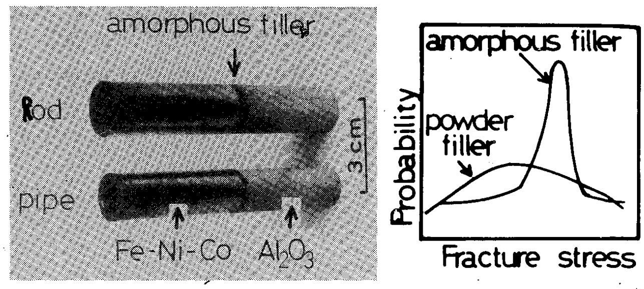
**Figure 39** is a general classification of composite material production techniques[39)] based on welding technologies, and this section will consider various composite manufacturing techniques and specific applications in producing ceramic-metal composites.

### 5.1 Composite technology as modifications of conventional methods

In brazing technique selection of the filler metal best suited to the base metals is difficult for bonding ceramics to metals. The importance of wetting the filler (metal, alloy, or ceramic) to the ceramic has led to adoption of techniques to improve wetting.

When a pure metal or alloy filler is used, brazing is performed in an inert, vacuum atmosphere with a filler metal containing an active, high melt point metal (e.g. titanium, zirconium, niobium). New brazing techniques use amorphous alloy fillers[40)] to bond such oxide ceramics as $Al_2O_3$ and non-oxide ceramics such as $Si_3N_4$ with various metals.

**Figure 40** shows chemical compositions of amorphous




| | Nominal composition (at%) | | | Liquidus temperature (°C) | Thickness (μm) |
|---|---|---|---|---|---|
| | Ti | Cu | Ni | | |
| Cu50Ti50 | 50 | 50 | - | 975 | 50 |
| Cu43Ti57 | 57 | 43 | - | 955 | 45 |
| Cu66Ti34 | 34 | 66 | - | 875 | 45 |
| Ni24.5Ti75.5 | 75.5 | - | 24.5 | 955 | 45 |

Brazing ceramics with amorphous filler metal in vacuum
( Excellent reliability, Easy brazing method)

**Fig. 40** Brazing using amorphous alloy filler.

alloy fillers used. The figure on the upper-left part, shows the result of alumina $Al_2O_3$ brazing, using these amorphous alloy filler. This filler is superior than the conventional powder as shown on the right.

Characteristics of amorphous fillers include (i) easy processing into thin films, rods, and other non-powder shapes, (ii) a constant filler structure which facilitates uniform application of the filler layer.

Use of oxide powders increases wetting of ceramic; $Al_2O_3$ brazing results[41)] using cuprous oxide ($Cu_2O$) powder are shown in **Fig. 41**. The bond was created by the formation of $CuAlO_2$ through a reaction at the interface of $Cu_2O$ and $Al_2O_3$. **Figure 42** shows cross sections of the brazed part[42)] in a vacuum ($5 \times 10^{-5}$ Torr) at 1200°C of different ceramics and of a ceramic and SUS 304 with cuprous oxide insert material. These brazing can also be achieved in air.

Solid state reaction bonding techniques are metal-metal

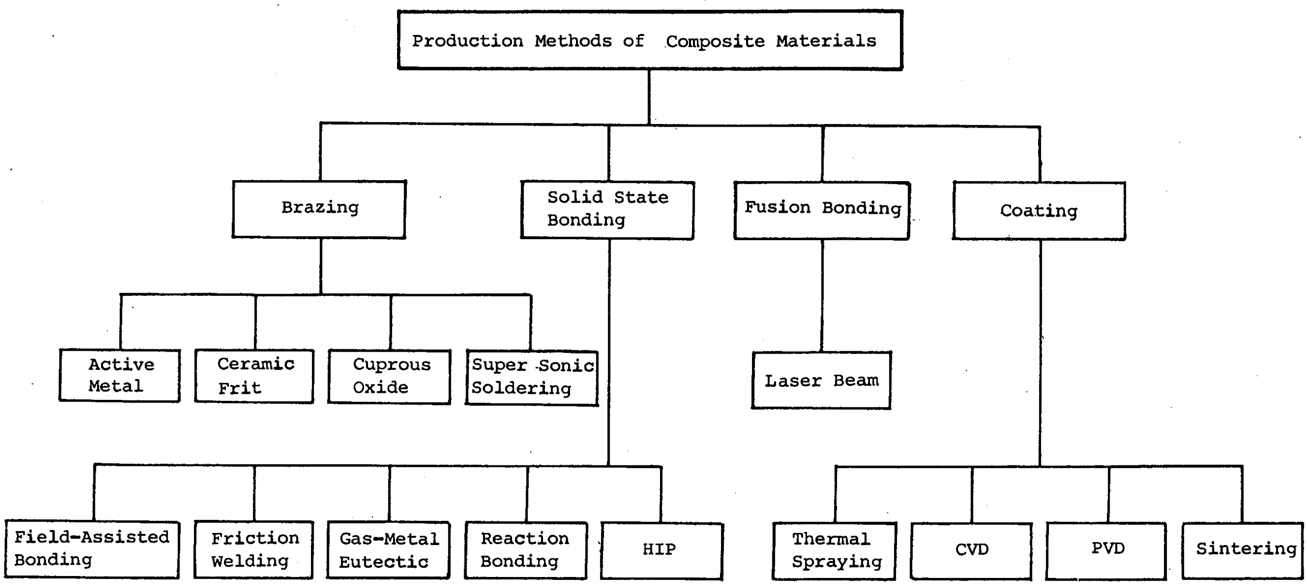



**Fig. 39** Classification of composit material production techniques.

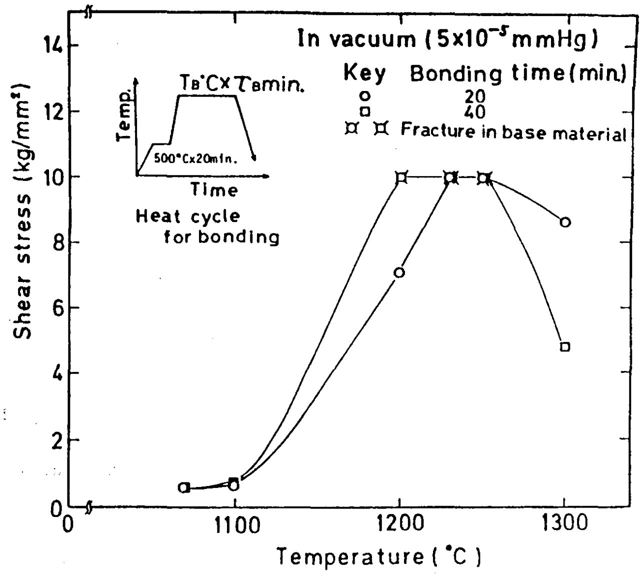



Fig. 41 Temperature dependence of shear strength of $Al_2O_3$ joint bonded by cuprous oxide method.

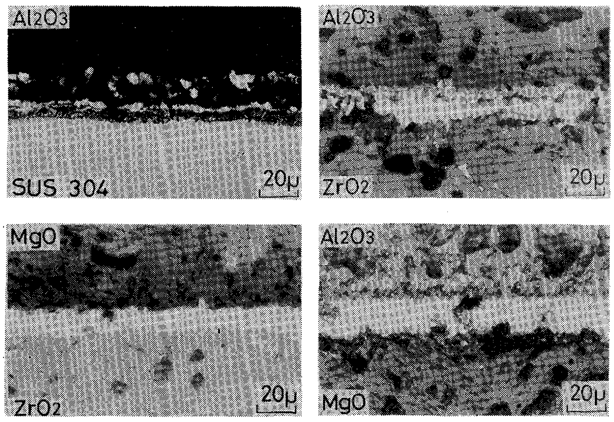



Fig. 42 Cross sections of brazed part of different ceramics and of a ceramic and SUS 304 bonded by cuprous oxide method.

diffusion bonding methods applied to the direct bonding of ceramics and metals. Chemical reactions induced by externally applied pressure and heat at the ceramic-metal interface are utilized to create the bond. Cross sections of pressurized, solid state reaction bonds[43] formed at 500°C in a vacuum between aluminum and various ceramics are shown in **Fig. 43**. This system also enables bonding in air, and the bond temperature is a major factor in the final bond. **Figure 44** shows composite bonds[44] of $ZrO_2$, aluminum, and titanium alloy. Although solid state reaction bonding techniques are being studied for bonding various combinations of ceramics and metals, they are limited by the bonding atmosphere. Friction welding[45] in air of ceramics and metals is also being studied as shown in **Fig. 45**. Field assisted bonding[46] in which a DC voltage is applied to shift ions in the ceramic and form a ceramic-metal bond using the solid electrolyte characteristic of ceramics is also being studied. **Figure 46** shows

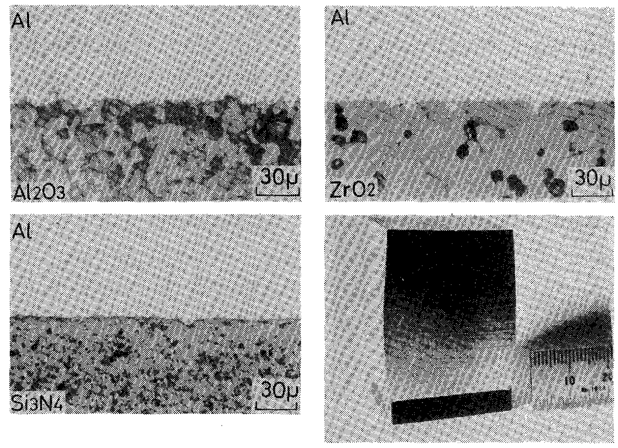



Fig. 43 Cross sections of bonded part of Al and various ceramics.

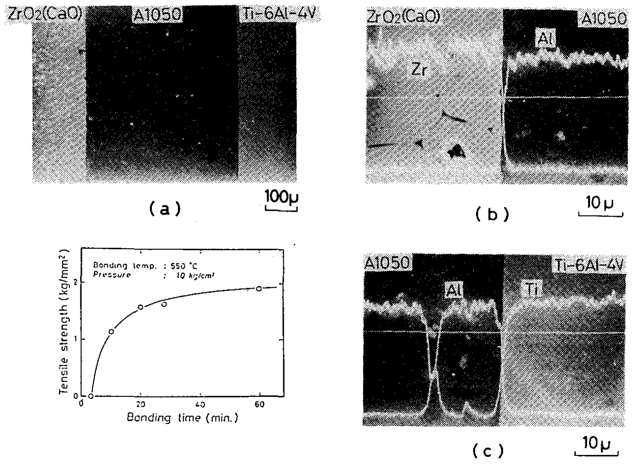



Fig. 44 Bond results of composite $ZrO_2$/Al/Ti alloy.

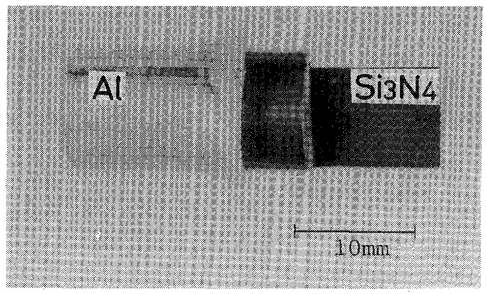



Fig. 45 Example of Al-$Si_3N_4$ joint (tensile strength; 15.9 kg/mm²) bonded by friction welding.

some examples[47] of pressurized field assisted bonding of glass and aluminum. This technique can be used for glass-semiconductor silicon, and $\beta$-$Al_2O_3$-metal bonding.[48]

As to the bonding of dissimilar materials a HIP process is increasing its importance in many industrial fields, and the method is expected to be potential and promissing in production and processing of new materials including ceramics and composite materials. **Figure 47** shows an example[49] of nozzles for injection molding made by HIP method.

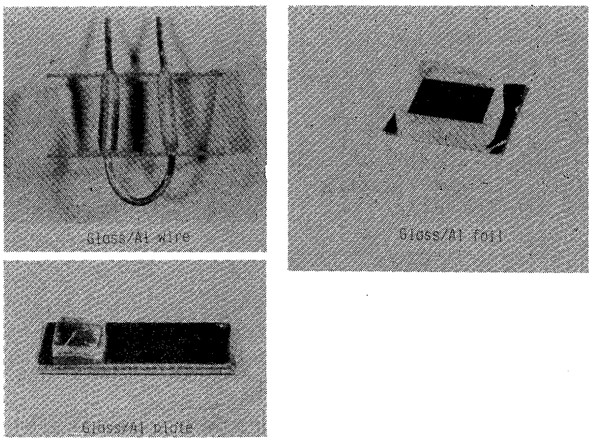


**Fig. 46** Appearances of joints made by pressurized field assisted bonding of glass on Al.

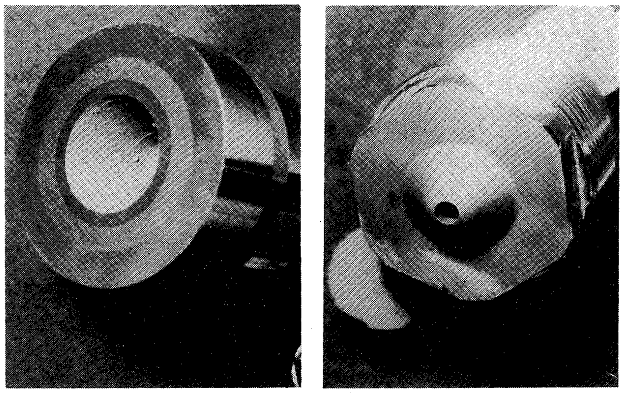


**Fig. 47** Nozzles for injection molding made by HIP method.

## 5.2 Composite technologies using high energy density beams

Research into ceramic fusion bonding applications of new high energy density heat sources are being conducted with laser beams. Results of tests on I-, L-, and T-Joints of $Al_2O_3$ formed with this technique[50] are shown in **Fig. 48**. Similar techniques using electron beams, and applications for bonding identical ceramics, dissimilar ceramics, and ceramic-metal composites are also being studied. The importance of these techniques is expected to grow for applications in composite materials production.

Thermal spraying is a composite materials production technology employing plasma and high energy gas flame, and surface coating techniques to bond ceramics and metals, ceramics and plastics, and other materials to manufacture composite materials offering new surface characteristics.

The functions provided by coating are widely accepted as the actual applications in many industries. **Figure 49** shows the samples[51] applied to sensor functions by ceramic plasma spraying. These sensors are used for measuring oxygen concentration in molten steel. The conventional sensor shown in the top of the left figure uses sintered $ZrO_2$. The needle sensors manufactured by ceramic spraying consist of a $Cr\text{-}Cr_2O_3/ZrO_2$ composite on a molybdenum rod. These new needle sensors offer significant cost reductions and reduced the response time.

The sign shown in **Fig. 50** was manufactured by ceramic plasma spraying of a ceramic-plastic composite.[52] Direct formation of a ceramic coating on plastic provides the heat resistance, wear resistance, and corro-

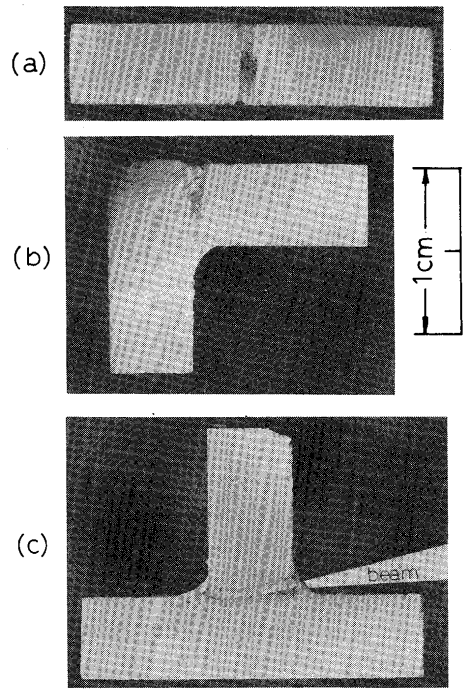



**Fig. 48** Bond results of $Al_2O_3$ with laser beam.

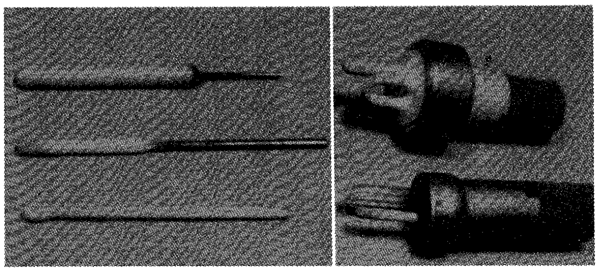


**Fig. 49** Needle sensor produced by thermal spraying (center) and tubular type sensor by sintering (top).


**Fig. 50** Ceramic-plastic composite produced by ceramic thermal spraying.

sion resistance of ceramics with the lower weight characteristics of ceramic-plastic composite.

While research into thermal spraying techniques capable of providing the surface of a base material with the characteristics of new ceramics is a relatively new field, the ability to manufacture composite structures featuring composite functions by simply coating the surface has been demonstrated, and the future importance of this field is expected to continue growing.

Other composite materials production techniques not covered here include FRP, FRM, and other ways to manufacture integrated composites, as well as coating techniques (e.g. CVD and PVD) which give new functions to the base material surface. The latter of these techniques in expected to become particularly important. While composite materials are being manufactured today using modifications of conventional welding techniques, composite material production techniques using laser beams and other high energy density beams will become increasingly important. Furthermore, these promise to be applied both as independent processing techniques and as composite processing technologies.

## 6. Other Applications of High Energy Density Beams

New heat source applications include the coating of conventional metallic materials with amorphous alloys and the manufacture of ultrafine ceramic particles.

Certain amorphous alloys are noted for extremely high corrosion resistance. Although conventional amorphous alloys can be quenched by ejecting the molten alloy on a high speed spinning roll, the shapes are limited to small test pieces.

Irradiation of certain alloys for a short time with a high energy density laser beam can convert the surface of the alloy into an amorphous structure. **Figure 51** shows the X-ray diffraction pattern of an Fe-10Cr-5Mo-P-8C alloy, the surface of which has been converted to an amorphous structure by laser irradiation.[53] In alloys containing higher phosphorous content more than 14 at % sharp diffraction peaks resulting from a crystalline structure are observed in the broad peak resulting from a noncrystalline structure. However, in alloys containing 13 at % P and 12 at % P, however, only broad spectrum resulting from the noncrystalline structure were found, indicating that these alloys are a noncrystalline alloy containing no crystalline structures.

Arc heat sources are also being used in the trial manufacture of ultrafine particles of metals and ceramics.[54,55] High concentrations of metal atoms are evaporated from the constricted arc root operated in molecular gases such as hydrogen or nitrogen which have high cooling effect on

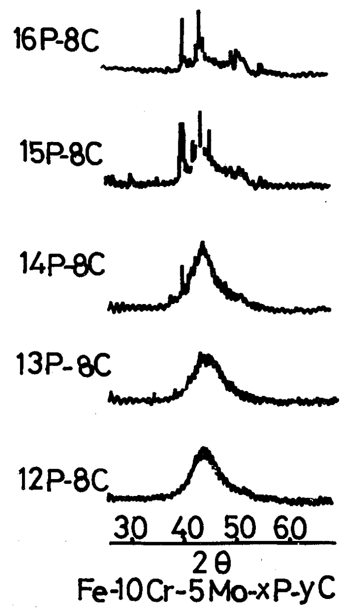



**Fig. 51** X-ray diffraction pattern of laser irradiated Fe-10Cr-5Mo-xP-yC alloy.

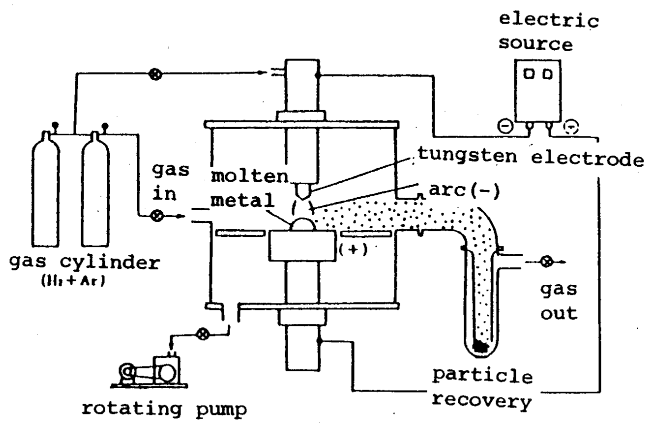



**Fig. 52** Apparatus for preparation of ultrafine particles.

arc, and they recombine to form ultrafine particles composed of many thousand atoms. The diameter of these particles is less than 0.1 $\mu$m.

This principle was used to design and manufacture the ultrafine particle production system shown in **Fig. 52**. Oxygen plasma can also be used for the plasma gas. Table 3 shows some products manufactured with an active plasma-liquid phase reaction process. Nitrides, oxides ($Al_2O_3$, MgO), carbides (SiC, TiC), and metallic ultrafine particles are represented. Mixtures of nitrides (TiN, ZrN) and metallic ultrafine particles can also be manufactured depending on the metals used, thus increasing expectations for production of new materials with refined functions. **Figure 53** is a photo taken with an electron microscope, of ultrafine particle of TiC exhibiting a crystalline NaCl structure. Characteristic crystal growth is recognizable.

**Table 3** Composition of ultrafine ceramic particle produced by nitrogen, hydrogen and oxygen plasma-liquid phase reaction method.

| Plasma Gas | Starting Material | Product (Ultrafine Particles) |
|---|---|---|
| Nitrogen | Ti, TiN | TiN (NaCl type) |
| | Zr | ZrN (NaCl type) |
| | Al, AlN | Al + AlN (Wurtzite type) |
| | Si, $Si_3N_4$ | Si (Diamond type) |
| Hydrogen | CaO | CaO (Lime), ($Ca(OH)_2$) |
| | MgO | MgO (Periclase) |
| | $Al_2O_3$ | $\alpha$-$Al_2O_3$ (Corundum) |
| | $TiO_2$ | $TiO_2$ (Rutile) |
| | $ZrO_2$ | $ZrO_2$ (Tetragonal>Cubic>Baddeleyite) |
| | SiC | $\beta$-SiC (Cubic) $\gg$ $\alpha$-SiC (Hexagonal) |
| | Ti + C | TiC (NaCl type) |
| | W + C | WC (Hexagonal) > $\beta$-WC (cubic) > $\alpha$-$W_2C$ |
| | $WO_2$ + C | WC > $\alpha$-$W_2C$ (Orthorhombic) |
| | WC | WC > $\beta$-WC |
| Oxygen | W | $WO_3$ (Monoclinic) |
| | Mo | $MoO_3$ (Orthorhombic) |
| | Nb | $Nb_2O_5$ (Monoclinic) or $NbO_2$ (Monoclinic) |

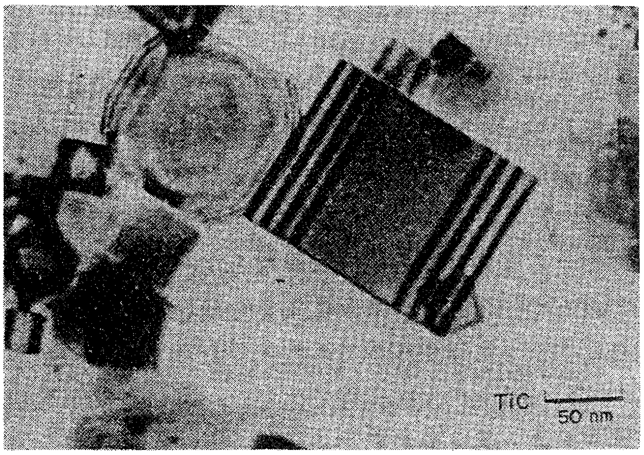



**Fig. 53** Electromicrograph of TiC ultrafine particle produced by activated plasma-liquid phase reaction method.

## 7. Summary

The paper reviewed current trends in the development of welding and its allied processes using electron beams, laser beams and plasma beams and contrasted the application of these with conventional welding heat sources, most particularly arc heat sources. In addition discussion was made on the relationship between these technologies and new materials development technologies. It has been also reviewed the current status of and future trends in robotics, a field indispensable to increased manufacturing flexibility, productivity, and assuring high precision and quality in welding joints and cutting. The discussion can be summarized in the following five points.

i) Future research in welding processes using high energy density beams can be expected to focus on the high performance and precision requirements. Examples of research into high precision and high performance welding include tandem electron beam welding and welding techniques combining computers and various sensors.

ii) Research into welding robots incorporating artificial intelligence was examined with reference to specific examples, and the future necessity for robots with artificial intelligence was demonstrated.

iii) Techniques using laser beams for surface modification like as nitriding and structural improvement of various metallic materials were introduced. The importance of electron beams, lasers and other high energy density beams in this field was also emphasized.

iv) In reviewing research trends in composite materials technologies, the production of composites through the bonding of ceramics and metals was given as an example of the importance of integrated composites and coating techniques. The role of high energy density beams will also be more important in these areas.

v) Amorphous alloys and ultrafine particles of ceramics and metals were offered as examples of new materials synthesis. The importance of reactive plasma and liquid phase reaction in ultrafine granule production were emphasized.

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